Investigating Auditorium Acoustics from the Perspective of Musicians

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Declaration of originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgment is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

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Paper 2, **Effect of a chamber orchestra on direct sound and early reflections for performers on stage: A Boundary Element Method study**
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Statement of ethical conduct

The research associated with this thesis abides by the international and Australian codes on human and animal experimentation, the guidelines by the Australian Governments Office of the Gene Technology Regulator, and the rulings of the Safety, Ethics and Institutional Biosafety Committees of the University.

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Abstract

This thesis investigates auditorium stage acoustics from the perspective of the performing musician, focusing primarily on chamber orchestras playing in a traditional concert setting. Stage acoustics has not been extensively studied in the past, and most studies have focused on full orchestras or small ensembles; however stage acoustics may be of particular importance to the musicians in a chamber orchestra as this is the largest group to perform routinely without a conductor. The aims of the study are to determine which subjective acoustic attributes are important to the chamber musicians and how auditoria could be assessed against these attributes. A broader goal is to inform auditorium and stage design for musicians. The study includes surveying of touring musicians, physical acoustic measurements on stage in auditoria, and modelling of sound propagation through a chamber orchestra with boundary element method (BEM) software.

Professional musicians were surveyed during concert tours to control for factors such as repertoire, instrument and position on stage and to minimise the limitations of short acoustical memory. The study encompassed 15 stages, including many of Australia's most important concert halls. High response rates resulted in statistically significant outcomes. Results indicate that the subjective attributes most correlated with overall acoustic impression are ensemble, support, timbre and reverberance. Reverberance was more clearly noted as important when auditoria with inadequate reverberance were included in the surveying set, however adequate reverberance alone was not sufficient for well-liked acoustics.

Physical acoustic measurements are often unavoidably made on empty stages, a significant simplification since the orchestra will impact the sound field. To investigate this a BEM model of a chamber orchestra was developed and compared to measurements of a chamber orchestra in situ in a concert hall. The study particularly focused on the degree to which the direct sound and first-order reflections were attenuated and altered by the presence

of the orchestra. For the 250 Hz octave band and higher, the empty and occupied stage results differed, particularly for the lateral reflections on stage, whereas the ceiling reflections produced comb filtering but were relatively unaffected by the orchestra. A tilted side wall case showed the orchestra has a reduced effect with a small elevation of the lateral reflections.

Musicians' overall acoustic impressions were compared to in situ physical acoustic measurements on the same stages using a 32-channel spherical microphone array, which allowed the directionality of the sound fields to be investigated. It was found that omnidirectional acoustic parameters (such as the well-known support measures) have some subjective relevance, which was more clearly observed when auditoria with optimum and non-optimum values were included in the dataset. In purpose-built auditoria with optimum reverberation and support parameters, it was found that the directionality of on-stage sound fields was subjectively important to musicians. A spatial parameter measuring very early sound energy from above relative to the sides and back was explored, and found to correlate at a significant level with musicians subjective ratings, with a preference for more horizontal energy from the sides and back on stage.

Overall, this study finds while stage parameters measured with an omnidirectional source and receiver (such as reverberation time and support measures) are useful in identifying musicians subjective preferences another important aspect is the directional distribution of early reflections on stage. The study examines acoustic conditions for musicians with in situ stage measurements and with BEM modelling, and identifies important aspects of stage and auditorium design for chamber orchestra musicians.

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Unless otherwise acknowledged the photographs in this dissertation have been taken by one of following persons: Lilyan Panton, Damien Holloway, Densil Cabrera or Lucas Dubinski. The candidate would like to thank these individuals for allowing the inclusion their photographs in this dissertation.

Preface

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Preliminary results from this thesis have been peer-reviewed and published as journal articles or in conference proceedings, see Panton et al. [2017], Panton et al. [2016], Panton et al. [2016a], Panton et al. [2016b], Panton and Holloway [2015], Panton et al. [2015] and Panton and Holloway [2014]. See Appendix A for further details.

Contents

Glossary

Terms and definitions

Clarity (Cl)	The degree to which musical details can be perceived by performers on stage. See also Gade [2015].
Communication with the main auditorium (Com)	The amount of communication between the stage and the main auditorium as described by the performer on stage.
Ensemble (Ens)	The degree to which musicians on stage can hear their own sound and the sound of others to play together with correct intonation and rhythmic precision. See also Gade [2015].
Hearing self (HS)	The degree to which musicians on stage can hear their own sound.
Impulse response	Response of a system (such as a room) to a single impulse containing the entire time-frequency information of the system.
Overall acoustic impression (OAI)	The overall impression of the acoustics on stage as judged by the performer.
p value	The p value is used to indicate level of statistical significance, between 0 and 1. If $p < 0.05$ the trend is considered statistically significant.
Reverberance (Rev)	The sense of subjective reverberance on stage, related to the rate of decay of sound to inaudible. An under reverberant space may be described as *"dry"* or *"dead"* and highly reverberant space may be described as *"wet"* or *"muddy"*. See also Gade [2015].
Support (Sup)	The degree to which the space support a musicians' effort to produce a tone from their instrument. See also Gade [2015].
Timbre (Tim)	The tonal colour of the sound on stage for the performer. See also Gade [2015].
Visual impression (VI)	The impression visually on stage for the performer. A space with poor visual impression could be described as *"unsightly"* whereas a space with an excellent visual impression could be described as *"gratifying"*.
Warmth (War)	The degree of warmth of the sound on stage for the performer (which may be thought of as one specific aspect of tonal colour). If the sound lacks warmth is may be described as *"bright"* or *"harsh"* and if the sound has warmth it may be described as *"warm"* or *"mellow"*.

Abbreviations

ACA	Adaptive Cross Approximation
ACO	Australian Chamber Orchestra
BEM	Boundary Element Method
Cl	Clarity
Com	Communication with the main auditorium
CS	Stage Clarity, see Equation 2.5.
DD	Directional Diffusion, see Equation 2.13.
Ech	Echoes
EDT	Early Decay Time
EEL	Early Ensemble Level, see Equation 2.4.
Ens	Ensemble
G	Sound Strength
G_e	Early Sound Strength, see Equation 2.8.
G_l	Late Sound Strength, see Equation 2.9.
HS	Hearing Self
IACC	Inter-Aural Cross-correlation
JND	Just Noticeable Difference
LF	Lateral Fraction
N	Number of samples in a dataset
N_O	Higher order Ambisonics order
OAI	Overall Acoustic Impression
R	Reflection coefficient
Rev	Reverberance
r_l	Correlation coefficient for a linear regression analysis
r_q	Correlation coefficient for a quadratic regression analysis
SPL	Sound Pressure Level
Sup	Support (subjective)
ST	Support (parameters)
ST_{early}	Early Support, see Equation 2.1.
ST_{late}	Late Support, see Equation 2.2.
TS_{20-50}	Top/Sides over 20–50 ms, see Equation 5.1.
TH_{20-50}	Top/Horizontal over 20–50 ms, see Equation 5.2.
SWC	Stage Walls Combined
Tim	Timbre
TH	Top/Horizontal Ratio
TS	Top/Sides Ratio
Vis	Visual Impression
War	Warmth
Z_s	Complex Impedance

Auditorium Abbreviations

AH	Adelaide Town Hall
ALB	Albury Entertainment Centre
AP	Sydney City Recital Centre, Angel Place
ARM	Armidale Town Hall
BEL	Bellingen Memorial Hall
CH	Lecture Theatre D, Coffs Harbour Education Campus
CLE	Auditorium at Redland Performing Arts Centre, Cleveland
DUB	Dubbo Regional Theatre
GLA	Gladstone Entertainment Centre
GOL	Gold Coast Arts Centre

GRI	Griffith Regional Theatre
HH	Hamer Hall
HL	Harold Lobb Concert Hall, Newcastle
HT	Hobart Town Hall
LH	Llewellyn Concert Hall
MC	Elisabeth Murdoch Hall, Melbourne Recital Centre
NAM	Nambour Civic Centre
PEN	Q Theatre, Penrith
PH	Perth Concert Hall
QC	Concert Hall Queensland Performing Arts Centre QPAC
QT	Queensland Conservatorium Theatre Brisbane
SO	Sydney Opera House Concert Hall
TAM	The Capitol Theatre, Tamworth
TAR	Manning Entertainment Centre, Taree
WAG	Wagga Wagga Civic Centre
WH	Wollongong Town Hall

Chapter 1

Introduction

Concert halls are spaces designed for the performance of music. The acoustics of purpose-built concert halls are carefully designed to provide an optimal listening experience for the audience. Past studies into auditorium acoustics have revealed subjective acoustic attributes preferred by audience members when listening to music in concert halls and objective acoustic measures have also been developed to quantify these subjective attributes (see Beranek [2004] and Barron [2009]). Musicians playing on stage in concert halls also experience the acoustics of the space, however the experience for musicians on stage is different to audience members and the acoustic needs and desires of musicians differ as well. Several key studies first investigated concert hall acoustics from the perspective of musicians, and began to reveal the impact of acoustics on the experience of musicians performing on stages in concert halls [Marshall et al., 1978, Barron, 1978, Gade, 1981]. Since these first studies, concert hall acoustics for musicians have typically been investigated in two ways: either through in situ acoustic measurements on stages and in situ surveying with musicians (such as studies by Gade [1989c] and Dammerud [2009]) or through listening and playing tests conducted in laboratory (such as studies by Gade [1989b], Ueno and Tachibana [2003] and Guthrie [2014]). Each method has advantages and disadvantages. In situ surveying of musicians ensures realism, with all the complexities of playing in an ensemble in a concert hall maintained. However, for in situ musician surveying repertoire, playing experience, on-stage position, instrument and acoustical memory cannot be fully controlled. Additionally, the acoustics in each hall will be unique and dependent on the position of the musician on stage, and a systematic study where a single design aspect is altered at once cannot be achieved. Laboratory studies of acoustics for musicians provide a controlled environment, where acoustic conditions can be carefully studied, however recreating a truly realistic playing experience in the laboratory is not possible, particularly when considering a larger ensemble.

Studies in the laboratory and in situ in concert halls have both led to the development of acoustic parameters, designed to quantify objectively the subjective preferences of musicians. Before discussing specific acoustic parameters, it is important to understand that when considering sound fields on stage (and in concert halls) usually the sound field is split into three sections based on time, and these three periods are referred to as 'direct sound', 'early reflections' and 'late reflections'. 'Direct sound' refers to the sound arriving directly from the source to the receiver, and for measurements on stage is usually also assumed to include a floor reflection (commonly defined with a time interval of 0–10 ms). 'Early reflections' refer to the period containing distinct or identifiable reflections after the direct sound up to some time period (50, 80 or 100 ms are often used as the cutoff between 'early' and 'late') and in some cases 'early' will be defined to include direct sound as well. The 'late reflections' (or 'late reverberation') is defined as those reflections arriving after the 'early' time period, which will be overlapping in time to produce a diffuse or reverberant sound field. The 'late' time period ends when the sound has decayed to inaudible (background noise levels). Musicians rely on reflections on stage for musical communication, and 'ease of ensemble' (or ease of musical communication) can be related to early arriving sound energy [Gade, 2007]. Musicians also desire a quality tone in a concert hall and for their sound to be supported, and these aspects can be related to late arriving sound energy [Gade, 2007]. Parameters to measure the strength of 'early' and 'late' sound on stage have been proposed, and these parameters are called the support measures (early and late support) [Gade, 1989c, 1992]. The support measures are the best known stage parameters and are included in part one of the international standard for room acoustic measurements [ISO-3382-1, 2009].

The support measures have been investigated in comparison to musicians' preferences in a number of studies and several such studies report low or no correlation between the support measures and musicians' ratings [Gade, 1989c, Cederlöf, 2006, Astolfi et al., 2007, van Luxemburg et al., 2009, Dammerud, 2009, Lautenbach and Vercammen, 2013]. The support measures are measured on stage with a 1 m source-receiver distance and with an omnidirecitonal source and receiver. Therefore while they distinguish reflections that occur in an early (20–100 ms) or late (100–1000 ms) time interval, the parameters do not specifically measure across-stage communication and do not consider the directionality of the sound fields on stage. Additionally, the support measures are either measured on an empty stage or a stage furnished with unoccupied chairs and music stands. Depending on the size of the ensemble the details of the on-stage sound fields will be impacted to different degrees by the presence of the orchestra itself, and empty stage measurements cannot account for this. Measurements are not usually undertaken on stage with an orchestra present because it is impractical due to expense and time. To investigate the impact of orchestras on on-stage sound fields it is more practical to use a model, and in the literature both scale and full-scale physical and computer model orchestras have been studied [Dammerud, 2009, Dammerud and Barron, 2010, Wenmaekers et al., 2016]. A small number of studies have also undertaken stage measurements with a real orchestra present [Halmrast, 2000, Skålevik, 2007]. These studies have found that while a large orchestra will significantly impact the early part of an impulse response on stage it does not do so in a systematic manner and is highly dependent on source-receiver path and also dependent on the sound frequency.

As mentioned above, another weakness of the support measures is that they do not consider the directionality of on-stage sound fields. Recently studies have investigated this issue further and begun to show that directionality of sounds fields on stage is an important subjective aspect for musicians playing on stage [Domínguez, 2008, Dammerud, 2009, Guthrie, 2014]. Dammerud [2009] found this indirectly by investigating ratios of stage dimensions (a preference for narrow and high stage enclosures was found), and Guthrie [2014] found this directly by conducting stage measurements with a spherical microphone array and performing listening and playing tests in the laboratory (a preference for low ratios of a parameter measuring early sound energy from top compared to from the sides on stage). So both these studies indicated that the ratio of on-stage sound energy from 'above' relative to the 'sides' may be related to musicians' preference when playing on stage in ensemble, with a preference for early lateral energy from the sides.

This dissertation focuses on chamber orchestra musicians (and to lesser extent chamber ensemble musicians), and considers professional musicians playing in purpose-built auditoria, as well as multi-purpose halls. Much of the previous work in this field has been on symphony orchestras. However, a chamber orchestra presents an interesting study group for several reasons. The chamber orchestras investigated in this study play without a conductor, and may therefore be even more reliant on good acoustics as they cannot use visual cues to synchronise and successfully play together. There may also be less variation in the opinions of musicians within a smaller playing group than in a large symphony orchestra, since there are fewer instrument types (predominantly strings) and also the chamber orchestra will use a physically smaller area on stage (less variation in acoustic conditions). This is relevant, as many previous studies have found that it is difficult to specify conclusive design criteria for musicians on stage because of confounding factors such as variation in acoustics around the stage and the impact of instrument played.

1.1 Scope and structure

This dissertation studies concert hall acoustics for chamber orchestra and ensemble musicians via subjective musician surveying, in situ physical acoustic measurements, and modelling.

In Chapter 2, previous research into stage acoustics for chamber ensembles, chamber orchestras and symphony orchestras is critically discussed. This review covers studies of stage and auditorium measurements and surveying with musicians, as well as laboratory studies and studies of the physical behavior of sound on stage for musicians (such as with scale modeling or measurements with an orchestra present on stage). The review provides the necessary background to the work completed in this doctorate, and will be referred to throughout.

In Chapter 3, surveying with various chamber orchestras is presented. In each survey the musicians took questionnaires on tour to avoid relying on acoustical memory (which is known to be short), and to control for factors such as repertoire, position on stage and instrument.

In Chapter 4, a model chamber orchestra was used to investigate the difference between on-stage sound fields with and without a chamber orchestra present. In this study, the direct sound and the first order stage enclosure reflections were investigated individually to demonstrate the effect of the chamber orchestra depending on arrival angle.

In Chapter 5, measurements conducted on stage and in the stalls in the same auditoria subjectively assessed by chamber ensemble and orchestra musicians are presented. The measurements were conducted with a spherical microphone array, which allows both traditional omnidirectional parameters and directionally-defined acoustic parameters to be derived. In Chapter 6, the measurement results are discussed in relation to musician surveying conducted, and key findings regarding how musicians' preferences can be assessed with stage measurements are presented.

Overall this dissertation identifies the key subjective acoustic attributes for chamber orchestra musicians, assesses how musicians and other stage objects impact on-stage sound fields, and investigates how on-stage acoustic measurements with a spherical microphone array can be used assess musicians' preferences, particularly by assessing the directionality of on-stage sound fields. The study is one of the first consider the directionality of sound on stage using in situ measurements and surveying with musicians. Additionally, the study focuses on chamber orchestras, which have not been widely studied in the past and which present an interesting and advantageous study group.

Chapter 2

Literature review

Research into auditorium acoustics over the past one hundred years has identified the acoustical attributes desired by listeners in the audience, and how these can be objectively quantified with acoustic parameters, see Barron [2009] or Beranek [2004]. More recently there has also been a focus on investigating concert hall acoustics from the perspective of the musicians who play on stage. Acoustics on stage are of clear importance to musicians as they try to hear one another, play together and create a quality tone in the space. Although it makes sense that initially interest in concert hall acoustics focused on the audience members who pay to attend concerts, arguably the acoustics on stage for musicians should be given the same level of focus as musicians are creating the music being enjoyed.

This dissertation primarily focuses on the acoustical experience of chamber orchestra musicians, playing in a traditional concert setting. Most past studies of stage acoustics have focused on symphony orchestras, or alternatively small ensembles or soloists. This literature review shall give an overview of past research relating to both small chamber ensembles and orchestras *and* symphony orchestras. At this point, the differences between a chamber ensemble, chamber orchestra and symphony orchestra are mentioned as these different playing groups will be regularly referred throughout this dissertation. A chamber orchestra is generally defined as a 'small orchestra' (between 12 and 40 players). A 'chamber orchestra' differs from a 'chamber ensemble', as a 'chamber ensemble' has fewer players (most commonly 3–5 players) and there is only one player per part, whereas in a chamber orchestra there may be more than one player per part. A chamber ensemble will operate without a conductor, and a chamber orchestra may or may not operate without a conductor. The chamber orchestras studied in this dissertation all operated without a conductor, such as the Australia Chamber Orchestra shown performing on stage in Figure 2.1. A symphony orchestra (or a philharmonic orchestra) usually has over 80 players. A symphony orchestra will always operate with a conductor. In this work, the focus has been on chamber orchestras (with the number of musicians between 15–30) performing without a conductor, and also chamber ensembles (such as a string quartet).

This literature review covers five major areas: 1) the physical behaviour of sound on stage, 2) the subjective experience of musicians on stage, 3) the acoustic stage parameters which have been proposed and used in past work, 4) those studies which have tested stage acoustics for musicians in a laboratory setting and 5) those studies which has tested stage acoustics for musicians with in situ musician surveying and in situ physical measurements in concert hall. The literature review demonstrates a significant amount of important past work has been undertaken regarding stage acoustics for musicians, however finally a section highlights some of the limitations of the work undertaken so far in this area.

Figure 2.1: An image of the Australian Chamber Orchestra performing on stage. Image courtesy of the Australian Chamber Orchestra [2017].

2.1 Sound behaviour and orchestras on stage

This section discusses physical sound behaviour on stage, including the impact of the musicians and other stage objects on on-stage sound fields. In an orchestra the presence of the orchestra itself leads to attenuation of the sound on stage, particularly the direct sound and early reflections. This affects how the sound of musicians' instruments propagates on stage. Previous studies have begun to quantify the effect of orchestras on on-stage sound fields, generally focusing on symphony orchestras setup on stage.

Dammerud and Barron [2010] completed an experimental study of on-stage attenuation, using a scale model (1:25) of a symphony orchestra playing on a 10 $\times$ 22 m stage, using source height of 1.0 m and receiver height of 1.2 m. In their scale model no stage shell was installed around the orchestra, meaning only attenuation of the direct sound and floor reflection was considered. Sound attenuation along three paths within the orchestra was examined, and particularly focused on the degree of sound attenuation between instrument groups known to have difficulties hearing one another. They found for two of the three paths considered the attenuation within the orchestra did not deviate significantly from the analytic solution for direct sound and floor reflection until the 500 Hz octave and above; however, for the third path deviation from the analytic solution was noted from 250 Hz and above. They found attenuation of -0.8 dB/m for source-receiver distances in the range 3–16 m at the 1 kHz octave band. They also analyzed full-scale measurements on a real stage with an orchestra, originally conducted by Ikeda et al. [2002], and found attenuation of -0.7 dB/m for source-receiver distances in the range 2–6 m at the 1 kHz octave band.

To validate this scale model, Dammerud and Barron [2010] tested a simplified configuration and compared results to unpublished full scale measurements undertaken by Krokstad et al. [1980]. Krokstad's full scale measurements with seated musicians involved a simplified case of two lines of seated people (one line with six people and one line with five people) in front of a source. The difference in sound pressure level (SPL) between a receiver placed behind the last person (8 m from the source) and a reference receiver at 1 m from the source was investigated. Three source heights were used (0.6 m, 0.9 m and 1.3 m) and average results from three source heights were presented in 1/3 octaves. The loudspeaker type used in measurements by Krokstad is unknown. Krokstad also did not provide any information on the precise location of the musicians between the source and the 8 m microphone, and did not state whether the measurements were undertaken in a room where surface reflections could impact the results. Despite these potential sources of error and ambiguity, Dammerud states that his scale model results were within +1 and -2 dB at 1 kHz and 2 kHz octaves respectively compared to the measurements by Krokstad et al. [1980]. However, Dammerud does not provide information on the agreement at other frequencies.

Skålevik [2007] also investigated sound attenuation within a symphony orchestra, and examined attenuation between a source (located at left-most first violin) and a receiver (located at rear-most bassoon player). The source-receiver distance was 11.7 m, and various source heights and receiver heights were used. This study undertook stage measurements with a symphony orchestra present (including seats, musicians, music stands and instruments).

Like Dammerud, Skålevik concluded that at 500 Hz and above the presence of the orchestra significantly attenuates the sound as it travels through the orchestra on stage.

Wenmaekers et al. [2016] have examined the effect of a symphony orchestra on stage, using a dummy orchestra consisting of mannequins (the sound absorption properties of these mannequins validated with measurements in a reverberation chamber). The dummy orchestra was used on fives stages, and attenuation of direct sound was examined to compare to results from Dammerud and Barron [2010]. Attenuation by the dummy orchestra was 3–6 dB greater than by Dammerud and Barron's scale model orchestra for the same source-receiver distances through the orchestra (distances between 3–16 m). Wenmaekers et al. also considered the effect of the orchestra on early sound parameters (namely ST_{early} and $ST_{early,d}$); the difference between occupied and empty condition was 2 dB for ST_{early} (slightly less for $ST_{\mathrm{early,d}}$ for a 1 m source-receiver distance). The definitions of the parameters ST_{early} and $ST_{early,d}$ are discussed in Section 2.3.

In a separate study, Dammerud et al. [2010] compared acoustic parameters on occupied and unoccupied stages using a scale model of a symphony orchestra, including a stage enclosure with a symphony orchestra setup on stage. The scale model stage enclosure was shoe-box shaped, and was altered by the addition of various scattering and diffusing panels. Also the impact of including a riser configuration was investigated. The investigation concluded that the acoustic response within 50 ms is strongly affected by the presence of a symphony orchestra on stage (when using source-receiver distances between 6–12 m). However, the study found that beyond 100 ms the impulse responses look similar. Dammerud's study also considered whether parameters were affected consistently with the introduction of the orchestra (independently of the stage enclosure condition and riser configuration used) — it was found that parameter defined with late time intervals (such as 100 ms–1000 ms) were the most consistently reduced; whereas, parameters defined with early time intervals (such as 7–50 ms) were highly dependent on the stage conditions and riser configuration.

Other work by Dammerud [2009] has used ray-tracing to model a symphony orchestra on stage, using the scale model results (including a scale model stage enclosure) for validation. However, Dammerud found poor agreement with the scale model for source-receiver distances between 5 and 9 m. In the ray-tracing model the musicians (and stands and instruments) were represented as simplified benches, and high scattering coefficients were applied so that the actual shape and angle of the benches had minimal impact on results. This ray-tracing orchestra model appears to be an inadequate model to investigate within-orchestra attenuation for source-receiver paths between 5 and 9 m (such as within a chamber orchestra), because wave interference effects, diffraction and specific characteristics of scattering are not fully accounted for by ray-tracing methods [Dammerud, 2009].

Halmrast [2000] undertook a study investigating colouration (changes in timbre) on stage for symphony orchestras, and completed measurements between player locations with a symphony orchestra present on the stage. The study suggested impulse response measurements must be taken on stages with the orchestra present to give realistic information about ensemble conditions and colouration.

No studies appear in the literature focusing on how a smaller chamber orchestra affects on-stage sound fields, or the applicability of standard stage measurements for such a group. Chamber orchestras, unlike symphony orchestras, typically rehearse and perform without a conductor, so arguably their acoustic needs are more critical, or at the very least different. Additionally, a chamber orchestra will often perform standing, whereas symphony orchestras perform seated, meaning different source-receiver heights are needed. Studies have focused on sound absorption by standing audiences and have considered the change in reverberant or late parameters with and without the audience present [Martellotta et al., 2010, Adelman-Larsen et al., 2010]. For an orchestra on stage it is important to consider how sound propagates through the orchestra (to consider ease of musical communication), as well the effect of the orchestra as a whole on audience measures.

Another consideration for sound behaviour on stage is the directionality of instruments within an orchestra. While instrument directivities will impact the sound field within an orchestra, it can be difficult to account for this in an objective analysis due to variations with instrument and even with the note played. The directivities of brass instruments have been found to be relatively consistent regardless of note being played [Otondo and Rindel, 2004]; however, this is not the case for strings (which are the instrument predominately used in a chamber orchestra). The directivities of musical instruments have been extensively measured by Meyer [2009], Pätynen and Lokki [2010] and Behler et al. [2012].

Sound delays on stage also impact the acoustics experienced by musicians. Due to the physical separation of players in a chamber orchestra (which can be 10 m), delays of up to 30 ms of direct sound can occur. Delays of more than 20 ms for direct sound have been found to be disturbing for players (discussed in Section 2.4). Lidar [2016] tested the relative importance of sight and hearing for synchronisation in a symphony orchestra, and concluded both sight and hearing are important for synchronisation purposes and that the orchestra configuration was important, noting the regardless of the configuration there was an improvement in synchronisation when musicians are seated closer together. In an orchestra the strings on either side of the centre of stage *must* begin playing simultaneously for their sound to reach the front of stage at the same time, although they will experience sound delay across the stage due their physical separation [Goodman, 2003, Dammerud, 2009]. However, in a smaller chamber orchestra (performing without a conductor), players cannot rely on the conductor to ensure strings on either side of the stage keep the same tempo despite experiencing delays of direct sound from each other. In this case the concertmaster (leader of 1st violin section) may take on the role of the conductor to a certain extent.

2.2 Musicians' subjective experience on stage

Studies have investigated musicians' impressions of stage acoustic conditions and identified the subjective acoustic attributes which are important to musicians playing on stage in auditoria.

A study by Gade [1981] interviewed 32 musicians (classical players including conductors, pianists, singers and orchestral instrumentalists) about different aspects of acoustic conditions. The most important aspects (ranked in order) were found to be: 'hearing each other', 'reverberation', 'support', 'timbre', 'dynamics', 'time delay' and 'change of pitch'. These aspects are reiterated as being the key subjective acoustic attributes for musicians playing classical music by Gade [2015]. Sanders [2003] found a similar result regarding chamber ensemble players; in this study examining correlations between various subjective attributes and 'overall acoustic impression' yielded the most significant attributes as 'support', followed by 'balance', 'ensemble' and 'reverberance'. Ueno et al. [2004b] conducted interviews with 14 chamber ensemble players to highlight which acoustical requirements are of importance for players in smaller ensembles. Two factors were found to be essential for ensemble players: 'hearing each other' and 'making harmony'. 'Hearing each other' was described in more detail by the players as the need to hear both their own sound and other players' sound. The players described the need for this attribute was related to keeping balance between instruments, synchronising the performance and making the melody heard. 'Making harmony' was the second important attribute and was described as the need for the sounds made by the different instruments to be in harmony. If this requirement was not met the players described that ‘the sound is separated’, ‘the sound is scattering’ or ‘the sound is not blended’.

Musicians’ acoustical needs and desires vary depending on the type of ensemble in which they are playing (such as a soloist, in a small ensemble, or a small or large orchestra). Gade [1981] noted for musicians playing in an orchestra the parameter of most importance is the ability to hear each other, while for soloists the parameters of most importance relate to sound quality. It was found that musicians usually listed these two aspects as their number one and number two priorities (the order being determined by their status as a soloist or orchestra player). Gade [1981] comments that this choice could be viewed as separating musicians into two groups: those who prioritise functionalistic qualities and those who prioritise aesthetic qualities.

Stage and auditorium acoustics are assessed by musicians who will each have their own individual playing background (such as years of experience, experience with different acoustics, among other factors), and thus personal taste may play a role in their experience. However, in Gade’s study the musicians interviewed reported they rarely had differences in personal opinions or differing ‘taste’ regarding on-stage acoustics — rather the musicians stated they put aside any personal preferences to work as one unit [Gade, 1981].

The acoustic experience of musicians in halls is complex, and musicians assessment of concert halls may be impacted by the way they can adapt to the acoustics without being fully aware of the process. Ueno and Tachibana [2005] undertook interviews with 13 professional musicians and developed a cognitive model of musicians’ perception in concert halls which described the way that musicians relate to the physical behaviour of a concert hall on an almost subconscious level, and come to be able to react to the acoustics of auditoria through ‘tacit knowing’ (which is the acquisition of a skill over time by repeating a task, without necessarily being able to describe how the skill was acquired). In a later study, Ueno et al. [2010] found through interviews that musicians feel they will adjust their performance based on room acoustics, such as by playing shorter notes in reverberant spaces and longer notes in dry spaces. It is clear that musician are affected by the acoustics of the space in which they play, and also will react and adapt, which adds to the complexity of subjective experience for musicians in concert halls.

A summary of the acoustical needs of musicians is outlined by Meyer [1994] in three levels of quality desired by performers:

- The lowest quality level simply relates to the musicians' requirements to be able to play correctly. If the player hears himself too loudly and others too weakly he is still aware of the harmonic cohesion of the whole and is able to play with correct intonation, although the rhythmic precision suffers. In the reverse, where the musician hears others too loudly, intonation is affected although rhythmic precision is still possible.

- The second quality level relates to the forming of sound quality. Good response of the musicians' instrument supports the musicians' security and enhances the accuracy of tone onsets and articulation, enlarges the dynamic range and avoids too much enforced tone production. Ease of hearing each other allows musicians to play with well balanced dynamics.

- The third level describes the sense of the orchestra playing as a whole and the integration of the entire sound of the orchestra. This relates to commonly produced articulation of chords and commonly formed dynamic structures. In particular strings require a sense of integration with their group. This level of quality may relate to the acoustic conditions at the conductor's position.

The above levels of quality are intended to relate to a large ensemble playing with a conductor; however, it is likely the first two quality levels will be equally applicable to smaller orchestras, while the third quality level may be of even greater significance to a small orchestra playing without the assistance of a conductor. With regard to the first point, in a small chamber orchestra it seems more likely that other musicians will be too weak rather than too strong; whereas, in a symphony orchestras others may become too strong (such as percussion and brass).

The nature of the human ears also means perceptual effects will influence the acoustic experience of musicians on stage. Three well-known perceptual effects should be considered:

- *Masking*: where louder sounds can mask quieter sounds and make them effectively inaudible. This is most prominent when the sounds are in the same frequency range, but low frequencies at high levels can also effectively mask higher frequencies. 'Simultaneous masking' refers to when two signals are basically simultaneous and the louder shall mask the quieter; whereas, 'temporal masking' refers to when signals occur at somewhat different times. In the case of temporal masking, a signal can mask noises that occur afterwards for up to 200 ms (forward masking) and can mask sounds that occur up to 20 ms before the masking signal (backward masking) [Kuttruff, 2009].

- *The Precedence Effect*: where when two sounds arrive at a listener the perceived direction of a sound source is based on whichever sound arrives first, as long as the later arriving sound is no more than 10 dB greater than the first [Long, 2005]. Assuming the sounds are of equal strength a time gap between sound arriving can be as low as 1 ms and a human will still perceive the sound to be coming from the direction of the first arriving sound [Long, 2005]. In relation to a musician playing on stage, if the direct sound is low compared to early reflections, the reflection may take perceptual precedence over the direct sound and this may cause directional confusion if the reflection is coming from a different direction to the direct sound.

- *The Cocktail Party Effect*: this effect describes the ability to focus one's listening attention to a specific sound source, when surrounded by multiple sound sources. Meyer [2009] states that the sound pressure level of the sound of interest must lie about 10–15 dB above the masking level, otherwise directional location is no longer possible. Additionally, this process is assisted if the musician can visualize the sound without hearing it; this visualization is what simulates the brain and the already existing stimulation pattern need only to be compared with the pattern arising from the arriving sound [Meyer, 2009]. The Cocktail Party Effect may actually be especially relevant to musicians playing on stage, as they try to isolate individual musical parts for synchronisation purposes, and they will generally be fully aware of the sound they are trying to isolate which will assist in the process.

Common stage acoustic parameters cannot account for the complexity of these perceptual effects, which, among other factors, may account for commonly low correlations seen between subjective musician preferences and acoustic parameters.

2.3 Acoustic measures proposed in previous studies

A number of acoustic stage parameters have been proposed in past studies. In some cases these measures have been adapted from audience measures, as defined in ISO-3382-1 [2009], and in some cases stage measures have been proposed based on work in laboratory experiments, which are discussed further in Section 2.4. This section gives an overview of many of the most widely used stage parameters, firstly considering omnidirectional parameters and then considering the fewer number of parameters defined to assess the directionality of on-stage sound fields.

2.3.1 Omnidirectional parameters

The most notable and widely used stage parameters are the support measures. The support measures were proposed by Gade [1989c] and later revised in Gade [1992]. Gade [1992] proposed early support (ST_{early}) as a measure to assess ensemble conditions, and late support (ST_{late}) as a measure to assess the impression of reverberation, and additionally also proposed total support (ST_{total}) to assess the support from the room for the sound from the musicians' instrument. The ST_{early} and ST_{late} measures are currently included in the international standard for acoustic measurements, ISO-3382-1 [2009], whereas ST_{total} has not been included. The ST measures are measured at 1 m from the acoustical centre of an omnidirectional source, using an omnidirectional microphone. The source and microphone should also be either 1 or 1.5 m above stage floor [ISO-3382-1, 2009]. Below are the mathematical definitions for the ST measures.

$$ST_{early}(ST1) = 10.\log_{10}\left(\frac{\int_{20\text{ms}}^{100\text{ms}} p^2(t).dt}{\int_{0\text{ms}}^{10\text{ms}} p^2(t).dt}\right) \tag{2.1}$$

$$ST_{late} = 10.\log_{10}\left(\frac{\int_{100\text{ms}}^{1000\text{ms}} p^2(t).dt}{\int_{0\text{ms}}^{10\text{ms}} p^2(t).dt}\right) \tag{2.2}$$

$$ST_{total}(ST2) = 10.\log_{10}\left(\frac{\int_{20\text{ms}}^{1000\text{ms}} p^2(t).dt}{\int_{0\text{ms}}^{10\text{ms}} p^2(t).dt}\right) \tag{2.3}$$

As can be seen above the time intervals for ST_{early}, ST_{late} and ST_{total} are 20–100 ms, 100–1000 ms and 20–1000 ms respectively. This assumes 20 ms is an appropriate cut off point between the direct sound (and floor reflection) and early reflections, and also that 100 ms is an appropriate cut off point between early reflections and late (reverberant) reflections. Gade [2010] states that the time intervals for the support measures have not been validated (meaning other time intervals may actually be more appropriate). The support measures are structured so that there exists a gap between 10–20 ms in ST_{early} where sound energy is not taken into a account. Due to this it is recommended that the transducer is placed a minimum distance of 4 m away from the stage boundary to avoid sound arriving within 10–20 ms [Gade, 1992]. Wenmaekers et al. [2012] notes that although it is suggested to avoid placing the transducer within 4 m of the stage boundary, seats and stands on-stage are allowed within 2–4 m from the transducer and this could result in reflections between 10–20 ms. With regard to measuring the ST measures in smaller rooms (i.e. in spaces not suitable for a symphony orchestra) the stage furniture should be removed and the 20 ms limit reduced [Gade, 1992].

Gade [1989c] investigated the validity of support measures through three studies involving on-stage measurements and surveying orchestras. The first and third studies showed significant correlations between the subjective results and the ST measures; however, the second study did not show any significant correlation between ST_{early} and subjective measures. Dammerud [2009] questions the validity of the first and second study undertaken by Gade, which is discussed further in Section 2.6. An additional study undertaken by Gade [1992] further examined the support measures and suggested the ratio between ST_{early} and ST_{late} may be useful for describing the degree of masking of ensemble information by late reflections. Giovannini and Gade [2007] studied the effect of adjusting stage enclosure setting on ST parameters, and found the parameters did not sensitive to setting changes (although it was somewhat dependent on position on stage). Hidaka and Nishihara [2004] studied ST_{early} on 18 stages, and found a high correlation between ST_{early} and stage volume ($r = 0.71$).

Gade [1989c] also proposed the measure EEL (Early Ensemble Level), which was originally intended to assess 'ease of ensemble'. This measure has the mathematical definition

$$\mathrm{EEL} = 10.\log_{10}\left(\frac{\int_{0\mathrm{ms}}^{80\mathrm{ms}} p_m^2(t).dt}{\int_{0\mathrm{ms}}^{10\mathrm{ms}} p^2(t).dt}\right). \tag{2.4}$$

The measure is obtained by measuring across the stage using two microphones, with one microphone for reference and the other for measuring the response across the stage. The reference microphone is at a distance of 1 m from the source. In Equation 2.4, p_m denotes that sound pressure picked up in a receiving position across the platform, but still integrated over a time interval starting at the time of emission. Thus EEL is a measure of efficiency with respect to level as well as time of the transmission of ensemble information among the orchestra members [Gade, 1989c]. It has been found that ST_{early} shows better correlation with 'ease of ensemble' and 'hearing of others' than EEL. Due to this lack of correlation between subjective measures and EEL, it has been omitted from Gade's later studies [Gade, 1992]. ST_{early} excludes direct sound (unlike EEL), which makes the parameter more sensitive to change in early reflections on stage (with change in reflective surfaces surrounding the stage), and this is a likely explanation for higher correlation between ST_{early} and subjective musician preferences.

Gade [1989c] also examined C_{80} (as defined in ISO-3382-1 [2009]) on stage, and called this parameter 'stage clarity' (or CS). C_{80} (or CS) is defined as

$$C_{80}(CS) = 10.\log_{10}\left(\frac{\int_{0\text{ms}}^{80\text{ms}} p^2(t).dt}{\int_{80\text{ms}}^{\infty} p^2(t).dt}\right). \tag{2.5}$$

Gade [1992] states that ST_{late} has replaced C_{80} (CS) as a measure to assess impression of reverberance on-stage, although C_{80} was investigated on stage by Dammerud [2009].

Wenmaekers et al. [2012] proposed extended versions of the support measures. These extended support measures were proposed to encompass the findings of a study into time interval limits and source-receiver distances for acoustic measures, and also to allow for measurement of support across stage (rather than only at 1 m). The extended ST parameters proposed contain a variable time point '$103 - delay$', which is used to take into account the delay of the direct sound for greater source-receiver distances. The 'delay' is computed as the source-receiver distance divided by the speed of sound. Thus the extended support measures by Wenmaekers et al. [2012] are defined as

$$ST_{early,d} = 10.\log\left(\frac{\int_{10}^{103-delay} p_d^2(t).dt}{\int_0^{10} p_{1m}^2(t).dt}\right) \tag{2.6}$$

$$ST_{late,d} = 10.\log\left(\frac{\int_{103-delay}^{\infty} p_d^2(t).dt}{\int_0^{10} p_{1m}^2(t).dt}\right) \tag{2.7}$$

where $ST_{early,d}$ is early support at distance d [dB], $ST_{late,d}$ is late support at distance d [dB], p_d is sound pressure measured at distance d [Pa], p_{1m} is sound pressure measured at 1 m distance [Pa] and $delay$ is source-receiver distance dived by the speed of sound [ms]. As can be seen in Equation 2.7, Wenmaekers et al. [2012] have altered the upper time limit to infinity (rather than 1000 ms) to make it conceptually clearer that the numerator in measure $ST_{late,d}$ relates to all the sound energy after the variable point '$103 - delay$'. Additionally in Equation 2.6 the lower time interval has been changed to 10 ms (from 20 ms) so that the measure can be undertaken closer to stage boundaries (within 2 m). As the time interval in which sound energy is captured is effectively shortened as source-receiver distance increases there is a limit to maximum source-receiver distance allowable for the measure. If a time interval width minimum of 30 ms is considered acceptable, then the extended support measures can be measured at distances up to 25 m. Wenmaekers et al. [2012] undertook an architectural analysis of an 'average stage' (based on average dimensions derived from the stages investigated by Dammerud [2009]). This analysis revealed that as the source-receiver distance increases the time interval between the arrival of the direct sound and the maximum first order reflection from the stage boundary narrows. This finding implies structuring measures so the time interval alters with source-receiver distances is a valid approach (it should be noted this was also a feature of EEL). Wenmaekers et al. [2012] recommend a transducer height of 1.0 m, and to have stage furniture (chairs and music stands) present for measurements. Wenmaekers et al. [2012] did not investigate whether $ST_{early,d}$ is an indicator of subjective impression of ensemble at various distances. Wenmaekers et al. [2012] did investigate how $ST_{early,d}$ changed with source-receiver distance on 11 stages and found $ST_{early,d}$ decays over distance with a clear logarithmic trend; thus demonstrating that early reflected energy on stage is distance dependant and correlates strongly to a logarithmic trend line using a variable time interval. Wenmaekers et al. [2012] found $ST_{late,d}$ does not vary with source-receiver distance, meaning an average value over all positions can be considered.

The sound strength parameter G has been used extensively in auditorium acoustics to assess subjective loudness, and is included in ISO-3382-1 [2009]. Variations on sound strength have been proposed and used in stage acoustics. Dammerud [2009] investigated G_e (G_{0-80}) and G_l ($G_{80-\infty}$), as defined in Equations 2.8 and 2.9 respectively.

$$G_e = 10.\log_{10}\left(\frac{\int_{0\text{ms}}^{80\text{ms}} p^2(t).dt}{\int_{0\text{ms}}^{\infty\text{ms}} p_{10}^2(t).dt}\right) = 10.\log_{10}\left(\frac{10^{C_{80}/10}.10^{G/10}}{1+10^{C_{80}/10}}\right) \tag{2.8}$$

$$G_l = 10.\log_{10}\left(\frac{\int_{80\text{ms}}^{\infty\text{ms}} p^2(t).dt}{\int_{0\text{ms}}^{\infty\text{ms}} p_{10}^2(t).dt}\right) = 10.\log_{10}\left(\frac{10^{G/10}}{1+10^{C_{80}/10}}\right) \tag{2.9}$$

As seen above, G_e is the energy of all the reflections arriving before 80 ms measured relative to the direct sound energy from an omnidirectional source when placed 10 m from the microphone in an anechoic environment, and G_l is the energy of all the reflections after 80 ms measured relative to the direct sound energy from an omnidirectional source when placed 10 m from the microphone in an anechoic environment. G_e and G_l can also be computed from the auditorium measures C_{80} and G. C_{80} and G are described in ISO-3382-1 [2009] as measurements for audience area only, but can equally be carried out with source and microphone on stage as well, as shown in Equations 2.8 and 2.9. G_e and G_l could be carried out on-stage at 1 m (similar to the support measures); however, Dammerud [2009] also conducted measurements at larger distances. Dammerud [2009] suggests source-receiver distances between 6–13 m for a symphony orchestra. By measuring G_e and G_l across-stage the aim is to measure the transmission of early and late sound energy within the orchestra. Gade [2013] comments that this was the intention of the measure EEL. Dammerud [2009] also investigated very early sound energy on stage using G_{7-50} which is defined as

$$G_{7-50} = 10.\log_{10}\left(\frac{\int_{7\text{ms}}^{50\text{ms}} p^2(t).dt}{\int_{0\text{ms}}^{\infty\text{ms}} p_{10}^2(t).dt}\right). \tag{2.10}$$

Thus, G_{7-50} is the energy of all the reflections arriving between 7 and 50 ms measured relative to the direct sound energy from an omnidirectional source when placed 10 m from the microphone in an anechoic environment.

A parameter proposed by Griesinger [1995], and also used by Dammerud [2009], is running reverberation or $RR160$. Griesinger [1995] undertook listening tests focusing on perceived reverberation, and found that some combinations of decay times and level were perceived as equally reverberant (longer decay times and low reverberant level may be perceived the same as shorter decay times and higher reverberant level). For a solo player, it was found that perceived reverberance was judged as equal if the energy between 0–160 ms and between 160–320 ms was equal. From this finding Griesinger [1995] proposed the following measure to assess perceived reverberation during musical performances

$$RR160 = 10.\log_{10}\left(\frac{\int_{160\text{ms}}^{320\text{ms}} p^2(t).dt}{\int_{0\text{ms}}^{160\text{ms}} p^2(t).dt}\right). \tag{2.11}$$

Although $RR160$ was found to gauge perceived reverberance for solo players, it was found that $RR160$ could not predict equal reverberance well for quartet or orchestral music. Dammerud [2009] also did not find $RR160$ to be subjectively relevant for symphony orchestras, and suggested this may be due to the poor physical validity of the sound on-stage between 0–160 ms without a symphony orchestra present.

A stage parameter was also proposed by van Den Braak and van Luxemburg [2008], and used to investigate the acoustics conditions for two different configurations on a stage in Portugal. They found that the ST measures did not point out differences in canopy positions, despite the conductor noting different acoustics depending on the canopy position. Thus the study aimed to find a new parameter which was impacted by change in configuration, and also further investigate ‘conductor acoustics’. van Den Braak and van Luxemburg [2008] proposed the following measure

$$LQ_{7-40} = 10.\log_{10}\left(\frac{\int_{7\text{ms}}^{40\text{ms}} p^2(t).dt}{\int_{40\text{ms}}^{\infty\text{ms}} p^2(t).dt}\right). \tag{2.12}$$

This measure is carried out with the sound source at different positions within the orchestra and a receiver at the conductor's position (both receiver and source are omnidirectional). The study found LQ_{7-40} was a useful parameter, which related to conductor's experience in the two halls investigated, as well as corresponding with the impressions of players. The measure LQ_{7-40} gives information about the amount of very early reflections. A later study investigated the time interval choice for measure LQ_{7-40}, and concluded the interval 7–40 ms was the most suitable to distinguish between most and least preferred halls, and that using a time interval of 7–80 ms limited the ability of the measure to distinguish between well liked and disliked auditoria [van Luxemburg et al., 2010].

2.3.2 Spatial parameters

A very limited number of studies have investigated the directionality of on-stage sound fields, however it is worth noting that directionally defined measures have been used in other applications. In terms of auditorium acoustics for audience members two spatially defined acoustic measures are included in ISO-3382-1 [2009]: Lateral Fraction (LF) and Inter-Aural Cross-correlation Coefficient (IACC). Lateral Fraction (LF) was originally proposed by Barron and Marshall [1981] to assess the impression of sound source broading. LF measures the fraction of energy arriving from lateral directions (either within 5–80 ms or after 80 ms) with a figure-of-eight microphone, and compares to the energy arriving from all directions (within 0–80 ms) as measured with an omnidirectional microphone. LF defined with an early time interval is defined to assess subjective 'apparent source width' and with a late time interval to assess subjective 'listener envelopment' [ISO-3382-1, 2009, Gade, 2007]. The parameter IACC is measured using a dummy head, and is measured to describe the dissimilarity of the signal arriving at the two ears (either for early reflections, 0–80 ms, or late reverberance, after 80 ms), see ISO-3382-1 [2009] for details. This parameter is also proposed to assess subjective 'listener envelopment' [Gade, 2007].

A spatially defined parameter has been proposed by Gover et al. [2004] to assess the spatial homogeneity in a room. The parameter is called Directional Diffusion (DD) and is defined as

$$DD = \left(1 - \frac{\mu}{\mu_0}\right) \times 100 \tag{2.13}$$

where μ is given by

$$\mu = \frac{1}{\langle e \rangle} \sum_{i=1}^{n} \mid e_i - \langle e \rangle \mid \tag{2.14}$$

where n is the number of beam directions and $\langle e \rangle$ is the incident energy averaged over n directions given by

$$\langle e \rangle = \frac{1}{n} \sum_{i=1}^{n} e_i. \tag{2.15}$$

The quantity μ_0 is the value of μ calculated for the anechoic impulse response of a single plane wave using the same array. Theoretically, a room that is completely anechoic will provide a value of 0% and a room that is completely isotropic will provide a value of 100%. This parameter may also be derived over varying time frames to show the change in isotropy over time. Guthrie [2014] used this parameter in an investigation of stage acoustics for musicians and focused on different time intervals, such as 0–30 ms (DD_{0-30}), see Section 2.4.

Guthrie [2014] investigated spatial stage parameters by defining spatial regions (called 'front', 'rear', 'top', 'bottom', 'left' and 'right'). Guthrie [2014] redefined many of the common stage acoustic parameters (such as the ST measures, LQ_{7-40}, G_e and G_l) based on these directional regions and also as ratios between directional regions. To capture sound energy from each region Guthrie [2014] steered beams in 21 evenly-spaced directions (2nd-order beams that overlapped at half power points), and summed the energy in each region. As stated Guthrie investigated many spatial version of parameters, one of which was LQ_{7-40} Top/Sides, which can be defined as

$$LQ_{7-40}\text{Top/Sides} = 10\log\left(\frac{\int_{7\,ms}^{40\,ms} p_{top}^2.dt}{\int_{40\,ms}^{\infty} p_{top}^2.dt}\right) - 10\log\left(\frac{\int_{7\,ms}^{40\,ms} p_{sides}^2.dt}{\int_{40\,ms}^{\infty} p_{sides}^2.dt}\right) \tag{2.16}$$

where p_{top} is the energy from the 'top' region and p_{sides} is the energy from the 'left' and 'right' regions, found with higher order Ambisonic (HOA) methods to produce spatial filtering. This study is discussed in further depth in Section 2.4, and a background to higher order

Ambisonics (HOA) is provided in Appendix F.

Directional versions of stage support have also been investigated by Cabrera et al. [2010], in a purely objective study investigating on-stage support with and without a stage set in a theatre. Cabrera et al. [2010] used a 1^{st} order microphone analysis of stage support to examine the directional acoustic effect of a stage set on a spoken word theatre stage (actors, like musicians, also benefit from acoustic support). Their approach used cardioid beamforming in the six axes (top, bottom, left, right, front, back), and simply adapted the conventional stage support parameters for directional analysis.

2.4 Laboratory experiments

Laboratory experiments involving simulated acoustic conditions have commonly been used to investigate musicians' preferences. The advantage of such investigations is that in a simulated acoustic environment the acoustic conditions can be controlled and rapidly altered to isolate specific influences on musicians' perceptions. Although, as discussed by Gade [2010] laboratory experiments are often overly simplified and do not recreate realistic acoustic conditions.

Gade [1989b] undertook experiments with the use of anechoic chambers and simulated orchestra conditions. In one experiment soloists were used, and the threshold of perception of a single reflections of the sound of their own instruments was investigated. As well as investigating soloists, small ensembles (flute/violin/cello trios) were used to investigate the effect of changing levels, delays and spectra of early reflections. Additionally, experiments relating to musicians sitting further apart in an orchestra were conducted (involving flute/violin and cello/violin duos), with use of two anechoic chambers. The effects investigated included changing the direct sound, early reflections and reverberation. From the soloist experiments it was found that for certain instruments early reflected energy (between 20–100 ms) of their own sound may be completely masked, due to the finding that the threshold of perception is 10–20 dB higher than the level of a single reflection from a hard surface. Despite this it was also found that an audible level of early reflections was preferred, and a certain amount of reverberation was also favoured. From the two ensemble related experiments, it was found that a delay of direct sound of more than 20 ms (equivalent to a 7 m distance) was disturbing for players. Additionally, a loss of high frequency sound and introduction of reverberant sound were found to negatively impact players mutual hearing. Dammerud [2009] comments that the lack of visual contact in Gade's experiment may have exaggerated the effects observed.

Meyer [1986] studied masking caused by the sound of the musicians' own instrument depending on the arrival direction of an early reflection, and the instrument played. It was found that violin players are more sensitive to reflections from within line of sight or from directly above, and less sensitive to reflections from diagonally above (at 1–2 kHz). The same finding was given for woodwind players at 2 kHz, where as 1 kHz woodwind players were sensitive to reflections arriving from the sides and above. In general, at low frequency (250–500 Hz) the directional dependence was minimal.

Guthrie [2008] also undertook experiments with players in separate anechoic chambers, but as well as transmitting sound from the other instrument (and artificially simulating different room acoustic responses) cameras and displays were used to allow visual communication between players. The visual communication was switched on and off as an experimental parameter. This study found that for good communication between players the 'self to other' ratio in sound levels is most crucial, followed by visual communication.

Naylor and Craik [1988] undertook laboratory experiments where musicians played in ensemble in anechoic conditions with pre-recorded accompaniments. This study found that as temporal and pitch differences increased the audibility of both the subject's own sound and the other player's sound increased. It was also found for good ensemble in chamber music that the sound of other should be heard at average levels between −23 and +5 dBA relative to one's own sound. Naylor [1988] expands on this and states the −23 to +5 dBA interval is for triple counterpoint playing, where as for unison and single counterpoint playing the intervals are −15 to +5 and −21 to +7 dBA respectively.

In a separate study, Guthrie [2014] undertook measurements in ten concert halls and theatres. The receiver used was a 16 channel spherical microphone array, allowing directionally-defined stage parameters to be investigated. Listening and playing tests were then undertaken with 17 musicians in the laboratory. Anechoic recordings were convolved with cross-stage impulse response measurements in auditoria, so as to recreate the experience of playing with an orchestra in the auditoria. In each case the orchestra was auralised as a single omnidirectional point source up-stage, and the player as a 'soloist' playing down stage. The relationship between musicians' preferences and spatially defined acoustic parameters were examined. The spatial parameters were examined at the 1 kHz octave band only, as the best spatial resolution could be achieved over this frequency range. It was found that low levels of early spatial homogeneity were preferred, corresponding to low values of DD_{0-30}. It was also found that musicians had a preference for lower values of LQ_{7-40} Top/Sides, indicating a preference for more early energy from the 'sides' and less from 'above'. Additionally, musicians were found to have a preference for increased Top EDT and decreased Rear EDT. Musicians were also found to have a preference for decreased $RR160$ from the rear of the stage.

Domínguez [2008] undertook simulations with soloists in an anechoic chamber. The soloists (two guitar players and one violin player) were asked to evaluate the acoustic conditions for six different sound fields. The participants were asked to evaluate in two different ways: give absolute evaluations on a rating scale for different attributes and give comparative evaluations between two sound fields experienced one after the other. The study focused on the fact the balance between the acoustic measures ST_{early} and ST_{late} can be similar for a 'wide and low' room and for a 'narrow and high' room and also examined whether the musicians' preferences were different to these different simulated conditions. The paired comparison tests showed musicians had a preference for the 'narrow and high' simulated room over the 'wide and low' simulated room - meaning they had a preference for close lateral reflections plus far ceiling reflections (instead of far lateral reflections and close ceiling ones). This finding agrees with the findings of Dammerud's [2009] study, which surveyed musicians playing in actual auditoria, as well as the finding from Guthrie [2014] that musicians preferred lower values of a top/sides parameters defined with an early time interval.

A number of laboratory studies have been conducted by Ueno and collaborators, who established a system of regenerating room impulse responses from real halls in an anechoic chamber [Ueno and Tachibana, 2003, Ueno et al., 2004a,b, 2010, Ueno and Tachibana, 2010]. This system involved measuring impulse responses in real halls with use of an omnidirectional (dodecahedron) source and six microphones (all at 90° to one another so that four microphones were in the horizontal plane and two were on a vertical line). The measured responses were then convolved with the direct sound from the instrument played in an anechoic chamber, and the resulting sound was played back into the same anechoic chamber from six loudspeakers, also all located at 90° from each other. This system allows the acoustic conditions of real concert halls to be simulated in a way which potentially is acoustically realistic. The advantage of this is that different simulated acoustic conditions can be rapidly switched between and also the simulated conditions from concert halls can be modified. The synthesised impulse responses in the anechoic chamber showed good agreement with real impulse responses and the acoustic measures derived from real and simulated impulse responses also agreed well. Ueno and Tachibana [2003] considered solo players on stage, and found they preferred a low level of early reflection and a moderate level of reverberant sound. Ueno et al. [2004a] considered the ensemble conditions for two distant players in an orchestra. This study involved two players playing in separate anechoic chambers. Impulse response measurements were still undertaken on a real stage, and the measurement locations were chosen to correspond to the concertmaster and a wind instrument player (source-receiver distance approx 6.7 m). The results for this study indicated early reflections *and* reverberation should be at an optimum level for the most preferred conditions for playing together. Ueno et al. [2004b] used a very similar approach to Ueno et al. [2004a]; however, focused on the acoustics on stage for chamber ensemble players, rather than for full orchestra players, and used a source-receiver distance of 3 m was used when measuring the actual concert hall impulse response. Various different instrument pairs were used in this experiment, and the musicians were asked to imagine they were playing on a real stage. Visual communication was provided with a video display in each room. The study found early reflections increase ease of hearing co-players' sound, and musicians were found not to be sensitive to change in reverberation time but instead more conscious of the magnitude of reverberation. Ueno et al. [2010] studied whether musicians will adjust their performance depending on the acoustics of the space, and identified that for professional musician differences in performance depending on the acoustics could be objectively identified, in terms of the tempo and the extent of vibrato. This work was continued in a second paper which found objective relationships between musicians' performances and acoustics, for example, it was found that for some musicians reverberation time correlated with the degree of *staccato* and with the silence duration between adjacent notes [Kato et al., 2015]. More recently, a three-dimensional sound field simulation system, known as a "Sound Cask", and consisting of 96 loudspeaker and 80 microphones, has been developed for reproducing the stage acoustics [Ueno et al., 2016]. An initial investigation of acoustic conditions of three stages indicated that the acoustic conditions on each stage could be reproduced, and subjectively differentiated by musicians in the study (although musicians' preferences regarding the acoustics were split).

Previous laboratory studies have generally involved only a few participants playing as soloists or with a small number of others, and an obvious criticism is that these conditions do not realistically replicate playing in a larger chamber or symphony orchestra.

2.5 Studies assessing musicians' preferences with in situ musician surveying and in situ stage measurements

This section discusses those previous studies which have focused on objective stage acoustic measures and musicians' subjective evaluations. The general method of analysis in these studies has been to survey one or more orchestras regarding a set of subjective attributes related to on-stage acoustics in auditoria, and following this to look for correlations between the musicians' subjective ratings and the objective acoustic measures. The majority of these investigations have studied symphony orchestras [Gade, 1989c, Cederlöf, 2006, Astolfi et al., 2007, Berntson and Andersson, 2007, van Luxemburg et al., 2009, Dammerud, 2009, Lautenbach and Vercammen, 2013]; however, several studies have focused on soloists or chamber ensemble players [Sanders, 2003, Chiang et al., 2003, Kim et al., 2010, Jeon et al., 2015, Kalkandjiev, 2015].

Sanders [2003] considered on-stage acoustics for chamber ensembles in auditoria in New Zealand. A total of 324 separate survey sheets were completed, by 22 participants, regarding 24 auditoria. The 22 participants were all highly experienced musicians and familiar with the auditoria of interest. A questionnaire was used which required musicians to indicate a point on a continuous linear scale. The questionnaires were completed from memory, there was no requirement for participants to have recently experienced the acoustics of the auditoria they were evaluating. The investigation found in poorly rated halls a linear relationship between 'overall acoustic impression' and 'reverberance' existed; however, in higher rated halls there was no significant correlation between 'overall acoustic impression' and 'reverberance'. This finding implies that when a certain quality of 'reverberance' is met other factors become more significant to 'overall acoustic impression'. Rectangular halls were found to be highly rated, while fan shaped halls were found to be lowly rated.

Chiang et al. [2003] studied chamber players (and soloists) and examined different on-stage configurations in five halls. The stage configuration was altered to reduce stage size (by placing additional side wall reflectors in front of existing side walls) and by changing the location of the musicians on stage. The subjective survey administered to musicians involved rating scales for 'hearing oneself', 'hearing others', 'ease of ensemble' and 'overall acoustic impression'. The decision to include only these four scales was based on the fact previous studies have shown players tend to judge on a single dimension. The objective measures specifically relating to stage conditions were undertaken on the five stages (ST_{early}, ST_{late}, $ED100$), as well as other measures usually used for evaluating audience conditions (G, C_{80}, T_s, $IACC$). The measure $ED100$ is simply a modified version of ST_{early} (the integration window of 20–100 ms is increased to 7–100 ms). This modified version of ST_{early} was used as on smaller stages 20 ms is too late to capture energy from walls close to the measurement position. This study found high correlation between all the subjective scales, particularly between 'hearing others', 'ease of ensemble' and 'overall acoustic impression', which indicates communication among players had the most significant impact on 'overall acoustic impression'. In terms of correlations between subjective evaluations and objective acoustic measures, a moderate correlation was found between 'overall impression'/'hearing oneself' and the early reflection parameters (T_{20}, ST_{early} and $ED100$). This moderate correlation was observed for some instruments (in particular piano), but not for others. The study also suggested that soloists and chamber groups might accept strong early energy; however, not much stronger than orchestra groups based on a preference found for $ED100$ values close to -12 dB, which is within -13 to -11 dB, the range of preferred values for ST_{early} found by Gade [1989c].

Another study which used a controlled experiment within an auditorium was undertaken by Kim et al. [2010]. The study noted that ST_{early} may range significantly across a single stage, for example ST_{early} was found to range between -18 and -8 dB on one stage studied by Jeon and Barron [2004]. Due to this it was considered that subjective tests on an actual stage platform could be an effective way of evaluating subjective relevance of objective measures, such as ST_{early}, ST_{late}, $IACC$ and stage clarity (CS). The study used vocalists and instrumentalists to subjectively evaluate stage acoustics with musicians playing at eight positions on stage. Two methods of evaluation were employed: paired comparison tests and ratings on a 5-point rating scale. The following aspects were evaluated with the 5-point rating scale: *Blending* (the degree to which one's performed music notes are blended by diffusivity of stage enclosure), *Support* (the degree to which the stage environment supports hearing oneself), *Size* (acoustically perceived hall size), *Directivity* (degree of spreading when one makes a sound) and *Reverberance* (perceived reverberation when one note or tone stops). The paired comparison test involved participants experiencing all the combinations of stage location pairs in a randomised order and determining which location from each pair was preferred. This information was then used to assign a 'scale value of preference' to each of the on-stage locations. Correlations between the 'scale value of preference' for each location and subjective parameters measured at the locations were examined. ST_{late} was found to be significantly correlated with the 'scale value of preference' ($r = 0.77$ for instrumentalists, $r = 0.82$ for vocalists), CS was found to be significantly correlated with the 'scale value of preference' ($r = -0.76$ for instrumentalists and $r = -0.72$ for vocalists), and $IACC$ (measured over 0-80 ms) was found to be significantly correlated with the 'scale value of preference' for vocalists only ($r = 0.77$). This study focused on the subjective impressions of musicians relating to the acoustical quality of hearing oneself, and did not consider mutual hearing.

Jeon et al. [2015] examined musicians' preferences with in situ testing of solo, duet and quartet performances, at six positions on stage, in two chamber halls. Acoustic measurements on stage were also conducted, focusing on the support measures. The study found soloists' preferences increased, while quartet performers' preference decreased, with stronger early and late reflections.

Kalkandjiev [2015] considered the experience of a soloist (cellist) in a field study of seven European auditoria. The study found the cellist adjusted his playing mostly to duration of reverberation (RT) and amount of reverberant energy (ST_{late}).

Silingardi et al. [2013] studied a trio and a chamber orchestra (of about 30 players), and undertook impulse response measurements on stage in Italian theatres. A questionnaire was completed by the musicians and correlation between measures (C_{80} and T_{30}) and various subjective scales were investigated. Very low correlations were found between increasing C_{80} and increasing ratings on scales such as 'ability to distinguish the sound of different instruments' and 'correct perception of the music played' and 'acoustic comfort' and 'overall impression'. However, as expected, T_{30} correlated well with 'perceived reverberation' and also 'overall impression'.

Gade [1989c] studied the subjective relevance of the ST parameters in three field experiments. In the first field study, Gade [1989c] studied the stage acoustics of nine halls with subjective assessments provided by three symphony orchestras. The stages were judged by different orchestras (except one stage which was judged by two orchestras), and a correlation was found between musicians' subjective ratings and ST_{early}. In the second field study, one visiting orchestra assessed eight halls in the United Kingdom and no correlation was found between musicians' subjective ratings and ST_{early}. In the third field study, modifications to a stage enclosure were tested and a correlation between musicians' subjective ratings and ST_{early} was found.

Table 2.1: Correlation coefficients (r) between orchestra average overall acoustic impression (OAI) and objective measures for Dammerud's first study of stage acoustics for symphony orchestras. Underlined indicates significance at a 5% level. Bold indicates significance at a 1% level. Total number of auditoria is N=12. See text for definitions of W_{rs}, H_{rb} and D.

	T_{30}	G_{late}	ST_{early}	W_{rs}	H_{rb}	D	H_{rb}/W_{rs}	D/W_{rs}
OAI	-0.24	-0.14	0.00	-0.52	<u>0.69</u>	0.39	**0.78**	0.55

Table 2.2: Correlation coefficients (r) between orchestra average overall acoustic impression (OAI) and objective measures for Dammerud's second study of stage acoustics for symphony orchestras. Underlined indicates significance at a 5% level. Total number of auditoria is N=6. See text for definitions of W_{rs}, H_{rb} and D.

	T_{30}	C_{80}	G_{late}	ST_{early}	ST_{late}	W_{rs}	H_{rb}	D	H_{rb}/W_{rs}	D/W_{rs}
OAI	0.25	0.28	-0.19	-0.09	-0.14	-0.79	0.67	<u>0.82</u>	<u>0.82</u>	<u>0.86</u>

Dammerud [2009] studied the impressions of symphony orchestra musicians performing on stage and undertook two separate subjective investigations: the first involved sending questionnaires to eight symphony orchestras (regarding a total of 45 auditoria) and the second focused on one symphony orchestra (which performed regularly in eight different auditoria). The first questionnaire administered to eight symphony orchestras was a general impressions survey, and was quite wide ranging and asked participants about many aspects, including non-acoustic issues, riser preference, loudness of others and ability to focus on particular instruments, awareness of reflective surfaces and importance of sound from audience area. The general impressions survey also asked participants to rank auditoria in which they regularly play for their acoustics for the performer, and thus provided 'overall acoustic impression' scores for a total of 45 auditoria. When comparing to objective acoustic data this list of ratings for 45 auditoria was shortened by removing those halls which were the orchestra's home auditorium (to avoid bias), auditoria which the orchestra had only visited a few times and also auditoria which were not purpose built for symphony orchestras. This left a list of 12 halls with which comparisons to available objective data were drawn. The comparison between objective acoustic parameters and this set of subjective data resulted in no significant correlations. However, correlations were found between subjective data and the on-stage geometry. The ratio between the height and the width of the stage was found to correlate with subjective preference; a high and narrow stage was preferred. These results are summarised in Table 2.1. It should be noted that Dammerud defined a stage dimension H_{rb} as the height of the ceiling from the average height of the brass and strings section, and another stage dimension W_{rs} as the average width of the reflecting surfaces at the location on stage where the strings sit. Dammerud also defined D as the stage depth.

In the second set of subjective surveying, Dammerud [2009] surveyed one symphony orchestra regarding the acoustics of eight auditoria in which they regularly played. Dammerud [2009] also undertook extensive objective measurements on the eight stages. Dammerud [2009] decided to exclude two auditoria from analysis based on the fact they were both theatres with very low reverberation times, and thus could not be considered suitable auditoria for a symphony orchestra. Based on the remaining six auditoria, correlations were found between objective parameters/stage geometry and subjective preferences, see Table 2.2. Again a preference for high and narrow stages was clear. However, it should be noted that following Dammerud's study, Gade [2010] reanalysed data from his original field study of stage acoustics for musicians [Gade, 1989c] and found no correlation between these architectural measures and musicians' preferences. In terms of objective measures, Dammerud [2009] found only parameters relating to 'reverberance' (T_{30}, C_{80}, G_{late} and ST_{late}) had any correlation with subjective rankings. These measures were found to be related to subjective scales of 'reverberance'. These objective acoustic measures could distinguish between the four most and least preferred halls, whereas the ST_{early} measure was found to be unable to make this distinction. Dammerud [2009] considered correlations between various subjective attributes and 'overall acoustic impression'. The correlation between 'hall reverberance' and 'overall acoustic impression' was found to be only moderate; however, if the two non purpose built auditoria were included in analysis the correlation was then higher ($r = 0.85$), which indicates the importance of reverberance may be hidden if only halls with optimum reverberance are considered. This agrees with the findings from Sanders [2003] for chamber ensembles.

Dammerud [2011] notes that an increase of G_{late} by more than 2 dB on stage relative to that in the stalls area corresponds to well-liked auditoria. Dammerud [2011] explains this by the fact an increase of 2 dB seems to correspond to a reflective stage enclosure, where reflections accumulate on stage. Equally, less than 2 dB increase appears to correspond to a highly absorbent stage enclosure, and poor acoustic coupling between main auditorium and stage. Dammerud [2011] concludes that comparing G_{late} on-stage and in the stalls area is relevant regarding acoustic coupling between stage and main auditorium, and for detecting an excess or lack of reverberant response provided by the stage enclosure within the different octave bands.

As well as Dammerud [2009], others have studied the correlations between on-stage acoustic parameters and the subjective preferences of symphony orchestra players, including Cederlöf [2006], Astolfi et al. [2007], Berntson and Andersson [2007], van Luxemburg et al. [2010]

and Lautenbach and Vercammen [2013]. In all these studies, omnidirecitonal source and omnidirectional receiver were used and low correlations between subjective and objective data found. Possible reasons for this are discussed further in Section 2.6.

Cederlöf [2006] undertook stage measurements in five auditoria purpose built for symphony orchestras, and also surveyed five orchestras which each considered one of the five auditoria their home venue. Dammerud [2009] added the data from this study to his results to increase the amount of information from which he could draw conclusions. Although Dammerud [2009] states that the study by Cederlöf [2006] was 'comparable' to his study, it must be noted that Cederlöf [2006] did not have stage furniture on-stage when measurements were undertaken and also surveyed orchestras regarding their home auditorium, whereas Dammerud [2009] included stage furniture for stage measurements and avoided surveying musicians about 'home auditoria'.

Astolfi et al. [2007] also undertook a study of the subjective preferences of five professional orchestras. The questionnaire administered to the orchestras consisted of two separate sections: the first relating to the musicians perceptions during playing in auditoria and the second relating to priority assessment of subjective attributes. The study examined correlations between objective data and subjective ratings and found a range of relatively weak correlations. Notably ST_{early} was not found to correlate with 'ensemble'; in fact both ST_{early} and ST_{late} did not correlate with expected subjective attributes (ST_{early} had a somewhat significant correlation with 'timbre' only and ST_{late} with 'dynamics' only).

Berntson and Andersson [2007] collaborated with a professional symphony orchestra to try to improve the acoustics of their home stage, and tested 14 configurations. Due to this collaboration, the objective measures were taken on stage with the full orchestra present. Having the full orchestra present on stage for measurements gave a rare opportunity to test the validity of objective parameters when taken under highly realistic conditions. The subjective judgments in this study were found to be highly scattered (and also found to be generally no less scattered within instrument groups), and this meant it was difficult to look for correlations between subjective and objective measures. Correlations to existing parameters (such as ST measures, EDT, C_{80} and IACC) were low.

van Luxemburg et al. [2009] undertook measurements on seven concert hall stages in the Netherlands. This study in part formed a further investigation into a previously proposed measure LQ_{7-40} [van Den Braak and van Luxemburg, 2008]. The study involved a student orchestra which played in seven concert halls on tour over a two week period. The surveys were completed directly after performances (i.e. did not rely on memory). On stage in the seven auditoria the following parameters were considered: T_{30}, EDT, G, ST_{early}, ST_{late}, LQ_{7-40}. This study concluded that there were no clear relationships observed between the acoustic parameters and subjective experiences. It was noted that the orchestra judged all the stages positively in terms of 'acoustic quality' and 'balance'; it is possible that as a student orchestra the participants were unable to be particularly discerning, due to a lack of experience and expertise judging auditorium acoustics.

Lautenbach and Vercammen [2013] undertook surveying with two symphony orchestras (one orchestra regarding the acoustics of three auditoria and another orchestra regarding the acoustics of six auditoria). Neither orchestra was surveyed about the same auditorium. Measurements were undertaken on the nine stages, in accordance with ISO-3382-1 [2009]. The stage was split into eight instrument groups and the centre of each group was chosen as a source and a receiver location. Measurements were also taken at the centre of each group with a source-receiver distance of 1 m. Therefore 64 impulse response measurements were undertaken on each stage. This study notes that average stage values of acoustic parameters are unlikely to characterise a whole stage (based on a previous study undertaken by Vercammen and Lautenbach [2009] which found ST_{early} to vary between -17 and -12 dB from the front to the back of the stage). The analysis of the subjective survey results and the acoustic parameters first focused on comparing stage average acoustic parameters and orchestra average scores for subjective attributes (such as 'loudness', 'hearing oneself', 'hearing others', and 'playing in time'). A range of weak correlations were found such as a negative correlation between perceived loudness and C_{80} averaged over 500–1000 Hz ($r = 0.71$), a positive correlation between ability to hear oneself and $ST_{early(10-100ms/0-10ms)}$ at 1 kHz ($r = 0.62$), a positive correlation between ability to hear others and $ST_{early(10-100ms/0-10ms)}$ at 1 kHz ($r = 0.61$), and a positive correlation between ability play in time and $ST_{early(10-100ms/0-10ms)}$ at the 1 kHz octave ($r = 0.51$). It should be noted that the study found stronger correlation with $ST_{early(10-100ms/0-10ms)}$ at 1 kHz than with $ST_{early(10-100ms/0-10ms)}$ averaged over 250–2000 Hz. Also it should be noted the study found stronger correlation for $ST_{early(10-100ms/0-10ms)}$ than for the usually used $ST_{early(20-100ms/0-10ms)}$.

2.6 Limitations of previous studies

As discussed in Section 2.5, previous studies into stage acoustics with in situ musician surveying and in situ measurements have had mixed success in meaningfully quantifying the subjective preferences of musicians. There is a wide range of possible explanations for this, generally relating to the limitations of the studies. First there are a number of issues in previous studies which have impacted upon the reliable collection of subjective data from musicians, such as the following issues:

- In previous studies, where musicians have not been surveyed during a touring schedule, the repertoire played by musicians in different auditoria could be variable, meaning musicians cannot make direct comparisons between auditorium's acoustics.
- In past studies, where musicians have not been surveyed during a touring schedule, reasonably long time intervals have existed between the musicians experiencing different auditoria, potentially making direct comparisons more difficult.
- Surveys have frequently been completed from memory, with no recent playing experience in the auditorium, rather than directly after experiencing the acoustics of the auditoria (even though acoustical memory is known to be short [Gade, 2007]).

It is difficult to control the issues mentioned above in order to keep conditions similar between different studies, and generally past studies have taken opportunities to survey musicians when they are available, without strict control of the above factors.

As well as the possible limitations surrounding subjective surveying, another contributing factor to poor correlations between subjective judgments and objective data is likely to be the limited number of auditoria which have been included in past studies. Generally the total number of auditoria included in recent studies has been low, particularly for studies of on-stage acoustics for symphony orchestras, and especially considering the increased complexity for a symphony orchestra on-stage compared to a chamber orchestra. The additional complexities include a greater number of different instruments playing on stage (potentially with differing acoustics needs), and a larger stage area being used (potentially with varied acoustics depending on on-stage location).

Dammerud [2009] considered eight auditoria in detail, and then shortened this list to six based on the fact two auditoria had very low reverberation times. Cederlöf [2006] considered only five auditoria, and used five different orchestras for the assessments. van Luxemburg et al. [2009] studied seven stages, with the use of a student orchestra for subjective surveying. Astolfi et al. [2007] examined five auditoria, again generally using different orchestras to assess different auditoria. Sanders [2003] considered the acoustics of 24 auditoria, and obtained some clear trends in the subjective data, but did not compare to any objective acoustic data, other than reverberation time.

The original studies undertaken by Gade [1989c] to investigate the ST measures (now included in the international standard for room acoustic measurements) were also limited by various factors, and Dammerud [2009] questions the validity of two of the three studies completed by Gade [1989c]. Gade's first study involved three Danish orchestras assessing nine auditoria, including their home halls. Dammerud [2009] criticises this study based on the fact different auditoria were assessed by different orchestras, with the exception of one hall (which was regularly used by two of the orchestras) *and* because it included 'home auditoria', which musicians may have been biased towards. The second study by Gade involved one Danish orchestra assessing eight auditoria in the UK. Dammerud [2009] criticises this study as the musicians only played in each hall once, which he considers is not enough experience to give a detailed assessment. Dammerud's [2009] final criticism is that Gade used auditoria purpose-built for symphony orchestras and also smaller halls with shorter reverberation times, meaning he altered both auditorium type and stage design simultaneously, making it difficult to isolate which influenced the subjective assessments.

In terms of the limitations related to laboratory experiments (rather than field experiments), Gade [2010] comments that many past experiments have been highly unrealistic and simplified to such a degree that they lack relevance to the actual acoustic conditions in auditoria. However, Gade [2010] does comment that the experimental set up used by Ueno shows much potential for undertaking laboratory experiments with subjective significance.

From past studies it appears that the use of omnidirectional source and omnidirectional receiver on stage as a method to obtain meaningful information regarding on-stage acoustic conditions has its limitations. Studies by Dammerud [2009], Cederlöf [2006], Astolfi et al. [2007], Berntson and Andersson [2007] and van Luxemburg et al. [2009] are all examples of investigations in which poor correlations between on-stage measures and subjective evaluations have been found. In part this may be attributed to the fact the finer details of acoustic response are impacted significantly by the presence of a symphony orchestra (compromising of 80 musicians) on stage, and thus using an empty stage to undertake measurements results will give a poor indication of the true acoustics experienced by musicians. Whether the effect of a smaller chamber orchestra is significant to on-stage sound fields has not yet been studied.

Additionally, omnidirectional stage parameters cannot consider the directionality of on-stage sound fields. Dammerud [2009] found ratios of stage dimensions (which in part account for directionality) showed high correlations with musicians' preferences. Additionally, a laboratory study which considered acoustic parameters defined with directionality was conducted by Guthrie [2014], and found that a parameter defined to assess energy from above relative to energy from the sides may relates to musicians preferences when playing in ensemble. This potential relevance of directionally-defined stages parameters has not yet been tested in a study considering on-stage acoustics in situ in concert halls.

2.7 Conclusion

This literature review has shown that a significant amount of previous research into stage acoustics has been undertaken, in the form of both field studies and laboratory work. In past work a significant focus has been on symphony orchestras and in a fewer number of studies on small ensembles and solo players. It appears a study predominantly focusing on chamber orchestras has not been undertaken. A chamber orchestra is the largest group to commonly perform without a conductor, unlike a symphony orchestra which would always perform with the assistance of a conductor. Additionally, a chamber orchestra does not contain loud brass or percussion instruments. Thus a chamber orchestra offers a notably different study group to a larger symphony orchestra.

Traditional omnidirectional stage parameters have been examined in comparison to subjective musician preferences in many past studies, in some cases low correlations have been observed, although generally there appears to be a relationship between musicians' preferences and parameters assessing late reflected sound or reverberant sound.

A small number of recent studies have used directional analysis of on-stage sound fields, or inferred information about directionality from stage geometry. These studies have shown that directionality of on-stage sound fields is important to musicians, and in particular indicated that the ratio of sound energy from above to sound energy arriving laterally on-stage may relate to musicians' preferences. However, current standardised stage parameters cannot account for directionality, and no study has systemically studied this with in situ stage measurements and musician surveying.

Chapter 3

Surveying chamber orchestra musicians on the acoustics of concert hall stages

3.1 Introduction

In this chapter the subjective surveying conducted with chamber orchestra musicians is presented and discussed.

As discussed in Section 2.6, a common issue with previous studies of auditorium acoustics from the perspective of musicians is a lack of quality subjective data from musicians. Frequently, studies have relied on different orchestras assessing different auditoria (meaning direct comparisons could not be made) and in other cases studies have relied on drawing conclusions from assessments in a very limited number of auditoria. Other studies have used musicians playing in the laboratory to investigate stage acoustics for musicians, but generally the acoustic conditions have been highly simplified or unrealistic [Gade, 2010].

In this study the Australian Chamber Orchestra (ACO) completed questionnaires about eight purpose-built auditoria in which they regularly play, during a tour in June 2015. Their sister group ACO2 (now known as ACO Collective) completed questionnaires about eight regional auditoria in which they played on a tour in May 2015. Additionally, ACO Collective (formerly known as ACO2) completed questionnaires about seven regional auditoria in which they played during a tour in September 2016. The sets of assessments were each made during a single concert tour, eliminating variables such as repertoire, and maximising acoustic memory through the short time between performances. These orchestras all perform without a conductor, hence arguably their acoustic requirements are equally critical to those in a symphony orchestra (where musicians play with some visual aid from the conductor). By asking musicians to complete the questionnaire on tour (and effectively controlling for factors such as repertoire, position on-stage and instrument played), several sets of high quality data from chamber orchestra musicians were obtained.

The internationally renowned ACO is Australia's premier chamber orchestra comprising elite musicians. On the surveyed tour they performed 16$^{\text{th}}$ and 17$^{\text{th}}$ century repertoire involving strings with woodwind and harpsichord, and including keyboard and violin solos (compositions by Lawes, Purcell, Bach and Haydn). Sister group ACO2 was established as an opportunity for Australia's most talented young professional musicians at the outset of their careers to gain experience in chamber orchestra performance. On the surveyed tour they performed repertoire ranging from the 18$^{\text{th}}$ to 21$^{\text{st}}$ centuries involving strings only, with a violin soloist in one work (Bach, Tchaikovsky, Barber and Berger). In 2016, ACO2 changed their name to ACO Collective, and were surveyed during a tour where they performed a cross section of repertoire for strings only from early 19$^{\text{th}}$ to 21$^{\text{st}}$ centuries. Although ACO2 and ACO Collective are nominally the same orchestra, there is a significant turn over each and year the majority of survey respondents would have been different for the ACO2 and ACO Collective datasets. The full details of repertoire, and other tour information, are given in Table 3.1 for the tours surveyed.

Initially the data collected from each orchestra are presented separately. The results from ACO are presented in Section 3.3, the results from ACO2 are presented in Section 3.4 and the results from ACO Collective are presented in Section 3.5. In these sections, the chamber orchestra datasets have been analysed in several ways:

- First, the difference between orchestra ratings for overall acoustic impression (OAI) have been considered (using post-hoc testing). This analysis indicates whether the musicians' judgments in different auditoria in terms of OAI differ significantly (for example at a 5% level). In part, significant differences indicate good agreement amongst the whole orchestra in regard to an auditorium's acoustics. This implies stage average values of acoustic parameters may be valid. Additionally, significant differences indicate acoustic parameters should be able to distinguish between the different auditoria; whereas, non-significant differences may indicate that musicians were not consistently detecting differing acoustics while on tour and therefore consistent subjective trends do not exist, and acoustic parameters are unlikely to correlate with musicians' impressions.

- Second, correlations between subjective characteristics and overall acoustic impression (OAI) have been examined. A high level of correlation between OAI and another subjective characteristic may indicate that this subjective characteristic highly influences ratings of OAI (i.e. it is an important subjective characteristic).
- Third, a qualitative analysis of the impact of instrument and position on stage on the musicians' ratings is provided.

Following this a principal component analysis (PCA) is presented for ACO and ACO2 datasets separately, as well as for the two datasets pooled together. The PCA analysis explores whether the individual attributes included in the questionnaire can be combined together into a fewer number of underlying variables (or principal components). The statistical analyses presented were carried out using the computer program R.

Surveying with chamber ensemble musicians was also conducted as part of this study. The data has been analysed qualitatively, because the number of respondents from each chamber ensemble was either 1 or 2 musicians (noting the chamber ensembles surveyed contained between 2 and 4 musicians) and presenting statistical analysis with such small sample sizes is not possible. The chamber ensembles were also surveyed during tours of purpose-built Australian concert halls, using the same methods as for ACO (and sister groups). The chamber ensembles names have not been provided to ensure the anonymity of the respondents. Due to the small number of total respondents in surveying with chamber ensembles is it difficult to generalise the findings, however it is interesting to compare findings to those from the chamber orchestras. The results from chamber ensemble musician surveying are summarised in Appendix B.

In Chapter 6 the subjective musician assessments discussed in this chapter are related to on-stage measurements; the on-stage measurements are first detailed in Chapter 5.

Table 3.1: Tour information for ACO, ACO2 and ACO Collective

Ensemble	Number of Respondents	Tour Dates	Repertoire
ACO	15	13–28 June 2015	**Purcell** The Fairy Queen: Suite **W Lawes** Consort set in 6 parts in C major **JS Bach**, Violin Concerto in A minor **Haydn**, Keyboard Concerto in D major, **Haydn**, Symphony No.44 in E minor
ACO2	15	14–27 May 2015	**JS Bach**, Concerto for Violin in E major, BWV1042 **Tchaikovsky**, "Souvenir de Florence" for String Orchestra, Op.70 **Barber**, Adagio for Strings **Herbert Berger**, Metropoles Suite for Violin and Strings
ACO Collective	9	2–16 Sept 2016	**Webern**, Langsamer Satz **Jaakko Kuusisto**, Wiima, Op.27 **Mendelssohn** String Symphony No.6 in E-flat major **Sculthorpe** Djilile **Beethoven**, (arr. strings) String Quartet in F major, Op.135

3.2 Surveying of musicians

3.2.1 Survey methods

The questionnaires were completed in conjunction with relevant tours of each orchestra or ensemble, so that the musicians would have played recently in the auditorium they were assessing. Additionally, this ensured the repertoire played in each auditorium would be consistent, allowing musicians to more easily compare the acoustics from each auditorium directly (without any impact from a change in the repertoire played). Each musician completed a separate questionnaire for each auditorium on the tour, and the questionnaire completed by a single musician were linked so individual musician trends could be examined as necessary. The survey method specifically tried to address the limitations of previous studies as discussed in Section 2.6, such as avoiding relying on acoustical memory, removing variables like position on stage, instrument played and repertoire, and avoiding the use of different ensembles to rate different auditoria.

The questionnaire itself asked musicians to rate auditoria on the following subjective scales: Overall Acoustic Impression (OAI), Hearing Self (HS), Support (Sup), Ensemble (Ens), Reverberance (Rev), Clarity (Cl), Warmth (War), Timbre (Tim), Communication with the main auditorium (Com), Echoes (Ech) and lastly Visual Impression (Vis). Additionally, the questionnaire asked whether there were any instruments which the player struggled to hear or could hear prominently. The questionnaire is shown in full in Figure 3.1. The questionnaire covers the mains aspects of auditorium acoustics which are known to be important to musicians [Gade, 2013, Dammerud, 2012, Sanders, 2003]. The questionnaire was deliberately kept as one page per auditorium, since the musicians were required to fill out many questionnaires and multiple pages per auditorium may have been perceived as too tiresome or time consuming. For each dataset obtained the response rate from musicians was high, and most musicians who participated completed all scales on the questionnaire – which appears to indicate the questionnaire was not considered unreasonably long by the musicians.

The questionnaire booklet also included a section where musicians were asked to provide some background information. An example background information page for the ACO Collective tour is given in Figure 3.2. The musicians were asked to indicate their instrument, whether they played a lead in the concert, their years of playing experience, and in cases where there was an ambiguity about position on stage musicians were asked to indicate where they were

Hall: xxxx ***Location: xxxx*** ***Concert Date: xxxx***

Overall Acoustic Impression	Very Poor		Very Good
Hearing Self	Difficult to hear own sound		Easy to hear own sound
Support	Feeling of "playing alone"		Sound "well supported". Easy to project.
Ensemble	Difficult to hear each other		Musical communication easy

Are there any instrument(s) which you struggle to hear in this venue? ____

Are there any instrument(s) which you hear particularly prominently in this venue? __________________________________

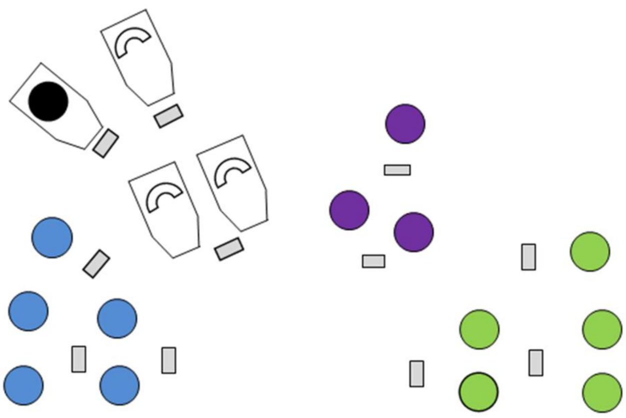
Reverberance	Dry	Live	Overly Reverberant
Clarity	Muddy		Clear
Warmth	Bright/Brilliant		Warm/mellow
Timbre	Unnatural		Natural
Communication with main auditorium	Insufficient sound from audience area		Sufficient sound from audience area
Echoes/ Disturbing Delays	Echoes audible/ Delayed sound disturbing		No audible echoes/Delayed sound not disturbing
Visual Impression	Unsightly/ repellent		Gratifying

Other comments:

Figure 3.1: Questionnaire

Your Playing Experience

1. How many years have you been playing professionally? _____ years
2. Which instrument do you play (including section for violins)? ___________________
3. Are you playing as a section leader for this tour? ___________________________
4. Please indicate where you sit/stand in the orchestra for this tour by circling one of the following locations:
   Note this information will be used to correlate your responses with the most relevant on stage measurements, and will not be published in a way which may identify you.



How to complete the questionnaires

- *Please complete the questionnaire as soon after playing or performing in the venue as possible.*
- *In the questionnaires you are required to indicate how you would rate the venue on several subjective scales. You need to draw a vertical line somewhere along the scale. As an example a completed scale is shown below:*

- *If you have any additional comments about the venue's acoustics you would like to provide there is room at the bottom of the survey.*

Figure 3.2: Background information page for ACO Collective tour

seated on stage. In the background section a completed subjective scale was shown as an example, and to demonstrate that when responding participants could mark any location on the subjective scales. The vertical lines on the subjective scales were simply provided to indicate position along the scale (see Figure 3.1). Therefore, the data obtained was effectively continuous, which is useful for post-processing the data (see Section 3.2.2). For the results presented in this thesis, ratings on each scale were converted to a number in the range 0–10, corresponding to the left and right limits of the scale, with a resolution of 0.1.

3.2.2 Data analysis considerations

As discussed in the introduction to this chapter, as part of the analysis of the subjective musician data correlation/regression analysis will be used to compare subjective characteristics and overall acoustic impression (OAI). When using survey data in a correlation analysis continuous data rather than categorical data is preferred [Miles and Shevlin, 2001], and it was for this reason that a continuous scale was used in the questionnaire, rather than a 5 point Likert Scale or similar. To conduct regression analysis we will assume that the data collected does not violate the assumption of independence, see Field et al. [2012]. It must be noted that in the dataset each musician will have completed multiple questionnaires and individual musician trends may exist, i.e. each individual musician may have their own *intercept* and their own *slope*, which would violate the assumption of independence. In this study musicians' questionnaires were labelled with a musician ID, so that if desired individual musicians' trends could be investigated. This differs to data collected by others, such as Dammerud [2009], where questionnaires completed by individual musicians were not linked and individual musician trends could not be considered. To fully account for individual musician responses a mixed model (multilevel model) would be needed. In this work such a model has not been implemented and individual musician trends have been effectively ignored. However, a visual inspection was used to examine whether the intercept and slope appeared to vary between musicians when comparing subjective characteristics and OAI, and overall slope and intercept appeared similar across musicians. As an alternative to using a mixed-model (which accounts for individual responses by giving each musician a different slope and intercept) some past studies have used normalisation of data to account for the way an individual musician uses the subjective scales [Jeon et al., 2015]. However, for the purposes of comparing OAI and the other subjective attributes it was deemed that normalisation was not needed, since each musician presumably used each scale in a similar way and all musician data was used when comparing OAI and other subjective attributes (see Section 3.3.2, 3.4.2 and 3.5.2).

3.3 Survey results with ACO

During the surveying tour, the Australian Chamber Orchestra (ACO) performed exclusively in major Australian purpose-built concert halls. For ACO the auditoria visited were Perth Concert Hall (PH), Adelaide Town Hall (AH), Sydney City Recital Hall Angel Place (AP), Llewellyn Hall Canberra (LH), Hamer Hall Melbourne (HH), Sydney Opera House Concert Hall (SO), QPAC Queensland Performing Arts Centre Brisbane (QC) and Wollongong Town Hall (WH).

From the ACO tour 15 out of a total 22 musicians completed the questionnaires (68% response rate). Included in the respondents from the ACO were six violins, two violas, two cellos, two oboes, two horns, and one double bass player. Figure 3.3 shows the orchestra average results and corresponding standard deviations for OAI in the eight auditoria for the ACO dataset. In Figures 3.4a and 3.4b the mean and median results for subjective characteristics for ACO are presented. From Figure 3.4b, we can see the order in preference in terms of median OAI is the same as for average OAI, with the exception of WH and QC. The median actually indicates WH was the least preferred auditorium. The written comments from musicians are included in Table 3.2; all musician comments are included here, with the exception of a few comments which are included and discussed in Section 3.7.

3.3.1 Differences in subjective characteristics between auditoria: ACO

This section considers which of the auditoria are judged as being significantly different in terms of OAI, based on assessments from the whole orchestra. This is of interest because if the orchestra as a whole judges the auditoria as being significantly different then it is more likely that acoustic parameters will be able to indicate orchestra preferences, whereas if the orchestra found minimal difference in the acoustic conditions in different auditoria then the potential for acoustic parameters to distinguish between auditoria will be limited.

Table 3.2: Comments from musicians regarding on-stage acoustics in auditoria for ACO tour

Auditorium	Comments
PH	‘Best concert hall in Australia!’
	‘Best acoustics’
	‘Warm Hall. Great.’
	‘Not the most attractive hall’
	‘I don’t mind playing here. It’s a generally good feeling, though a little lonely in a small ensemble. I trust it sounds ok out in the hall though.’
AH	‘I love playing in this hall’
	‘Excellent venue’
	‘Nice Hall’
	‘Lovely hall to play in ... when sitting further back on stage I am finding it hard to hear other at the front of stage. At the front of stage it is great to hear and play. Best for smaller ensembles as bass/wind very reverberant and favoured.’
	‘Good size hall. Not too big. Little bit too washy at times.’
AP	‘Small stage, horn and bass sound will tend to bounce off walls’
	‘Cold, harsh hall. Everything is metallic and cold’
	‘I really enjoy playing here. Sometimes I worry the winds get lost a little but it’s a very comfortable, supportive acoustic to play in.’
LH	‘In loud passages difficult to achieve togetherness’
	‘Difficult to hear across stage close players are overly loud’
	‘Horns hit the back wall easily’
	‘A bit distant on-stage’
	‘Difficult to hear other side of the orchestra’
	‘Feeling of playing alone, “distance” from other musicians is the most problematic aspect. Quite cold sound also.’
	‘The hall feels quite different with the audience, for my part it feels more uncomfortable. There is a lot more warmth and balance and the balance of what I hear back from the group is better’
HH	‘This hall is too big’
	‘This hall has a breeze on stage. It’s noticeable in concerts and make things difficult.’
SO	‘Difficult to hear across the stage’ ’
	‘I’ve played here a lot. It’s noticeably more difficult to play with good ensemble than AP. Difficult to hear those at the front of the stage, and you can’t trust that what sounds together on stage is in the hall.
	‘Cold, harsh hall that doesn’t pick up on any warmth, vib, portamento, etc. Ruins music for violinist. Everything is metallic and cold.’
QC	‘Dead hall’
	‘Sound is much worse in the hall than on the stage’
WH	‘Not the most beautiful hall but good for a small sized city. It feels very live on stage but I get the impression the result in the hall is better than on stage.’
	‘Very loud!’
	‘The stage is not level’

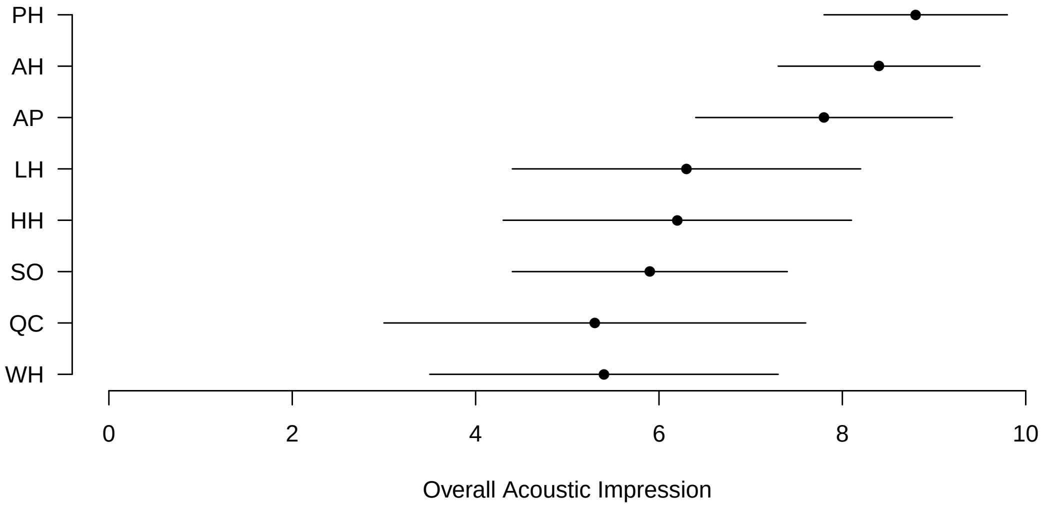
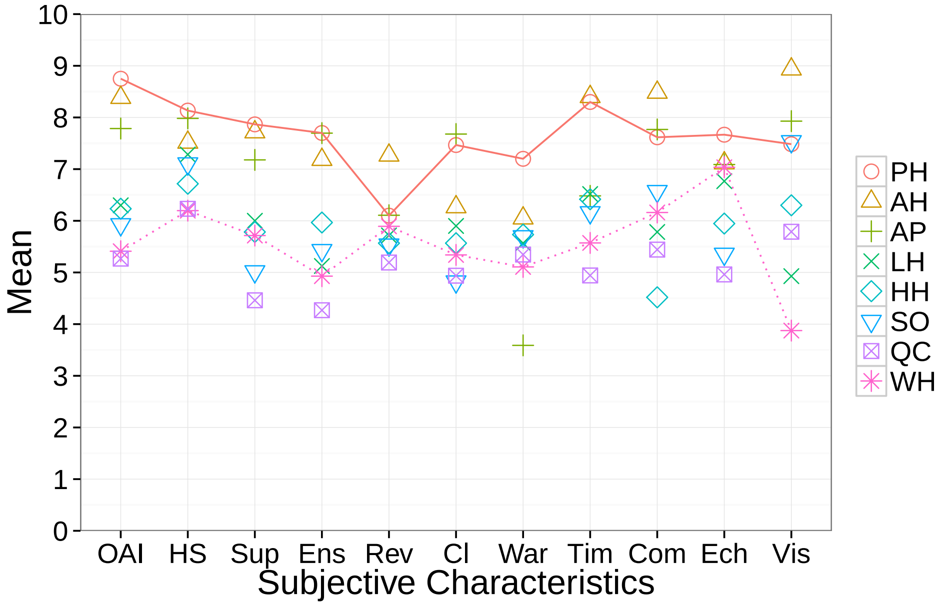


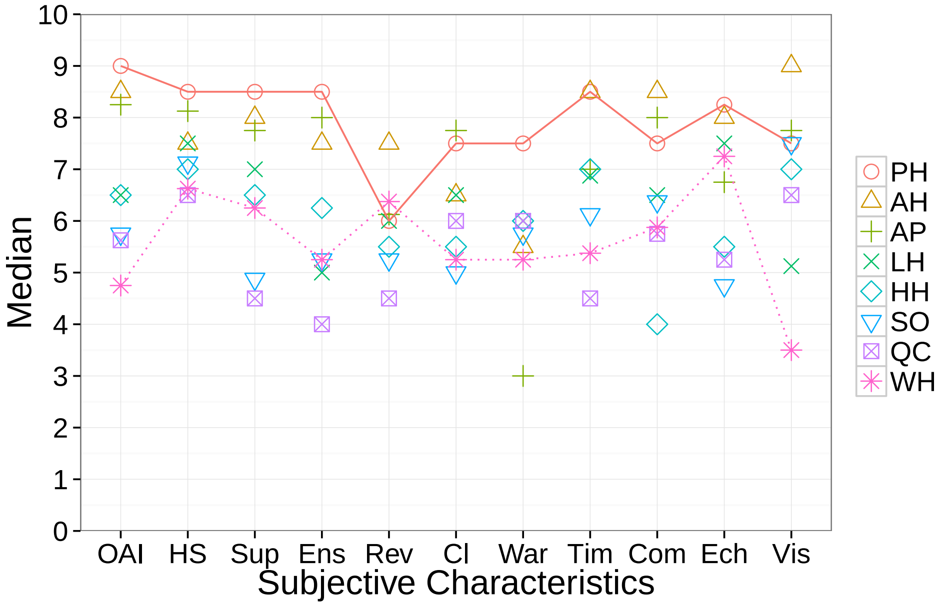
Figure 3.3: Mean and standard deviation for ‘Overall Acoustic Impression’ in each auditorium for ACO

Additionally, this analysis may help to indicate whether orchestra average values for OAI are valid. If individual musicians assess the same auditorium differently then it is less likely significant differences would be found between auditorium assessments when considering the orchestra data as a whole. This may indicate that musician preferences based on instrument group or on-stage position need to be considered.

Post hoc testing was conducted, and a Holm correction applied due to multiple comparisons, see Field et al. [2012]. To test homogeneity of variance within the data, the Levene Test was conducted and the result confirmed this assumption was met. Table 3.3 summarises the p values for differences between orchestra assessments of OAI in auditoria for the ACO data. PH is rated significantly above all auditoria in the study, except AH and AP (at either a 1% or 5% level). Similarly, AH is rated significantly above all lower auditoria in the study, except AP (at either at 1% or 5% level). The other auditoria are more difficult to distinguish between. QC and WH for example are only significantly worse than the three most preferred auditoria: PH, AH and AP (at either at 1% or 5% level or 10% level). It appears to be quite difficult to conclusively distinguish between the lower rated auditoria in the study: LH, HH, SO, QC and WH.



(a) Average orchestra assessments for subjective characteristics in auditoria, for ACO. A solid line is shown through the data for the highest rated auditorium (PH) and a dashed line through the data for the lowest rated auditorium (WH).



(b) Median orchestra assessments for subjective characteristics in auditoria, for ACO. A solid line is shown through the data for the highest rated auditorium (PH) and a dashed line through the data for the lowest rated auditorium (WH).

Figure 3.4: Average and median for subjective characteristics for ACO

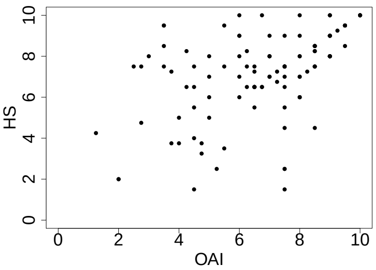
Table 3.3: p values (adjusted with Holm) for difference between orchestra assessments of OAI in auditoria assessed by ACO. Bold numbers indicate significance at 1% level ($p < 0.01$), underlined significance at 5% level ($p < 0.05$).

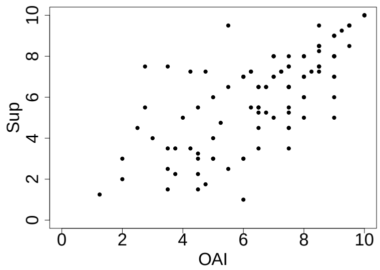
	PH	AH	AP	LH	HH	SO	WH
AH	1						
AP	0.49	1					
LH	<u>0.022</u>	<u>0.017</u>	0.458				
HH	**0.005**	<u>0.042</u>	0.458	1			
SO	**0.000**	**0.003**	0.069	1	1		
WH	**0.004**	**0.002**	0.09	1	1	1	
QC	<u>0.011</u>	**0.001**	0.094	1	1	1	1

3.3.2 Subjective characteristics related to overall acoustic impression: ACO

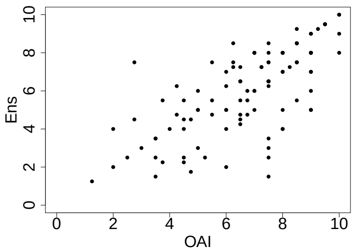
It is of interest to gauge how Overall Acoustic Impression (OAI) correlated with the other subjective characteristics. A high level of correlation between OAI and a subjective characteristic may indicate that this subjective characteristic highly influences ratings of OAI (i.e. it is an important subjective characteristic). To examine these trends a correlation analysis has been conducted. Firstly the subjective data scales and OAI have been plotted against each other, as shown in Figure 3.5. Additionally, a correlation matrix has been produced to examine relationships between OAI and the other subjective scales, as well as any relationships between all the other subjective scales. The correlation table for ACO is shown in Table 3.4. The correlation coefficients have been computed using all the available musician data; the number of samples (N) varies due to missing data, where musicians have not completed all the relevant subjective scales.

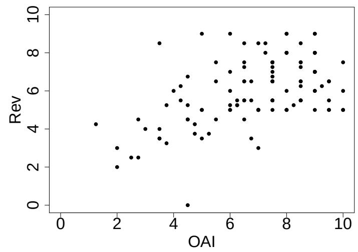
For ACO most of the subjective scales were significantly correlated with OAI. The most highly correlated were: ‘support’, ‘ensemble’ and ‘timbre’ (r between 0.68–0.73). These results, in comparison to the other musician survey results, are discussed in Section 3.7.



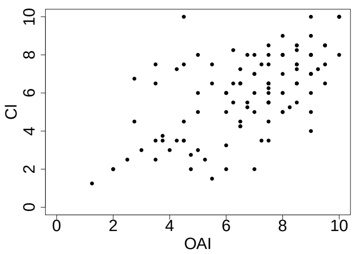


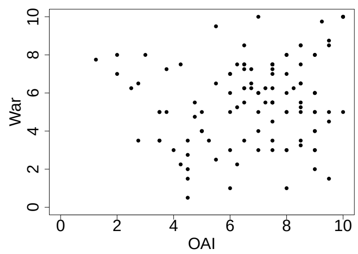
(a) HS vs. OAI, r =0.48, N =116, p <0.01 (b) Sup vs. OAI, r =0.73, N =115, p <0.01



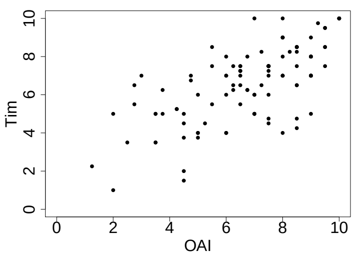


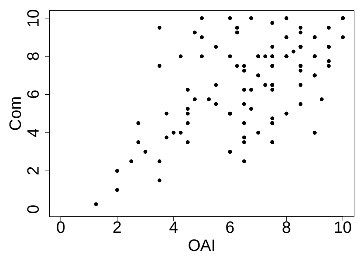
(c) Ens vs. OAI, r =0.71, N =114, p <0.01 (d) Rev vs OAI, r =0.50, N =115, p <0.01



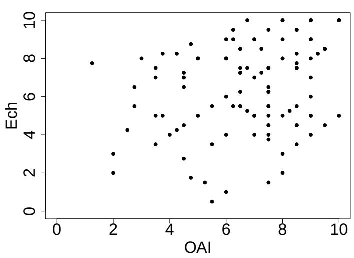


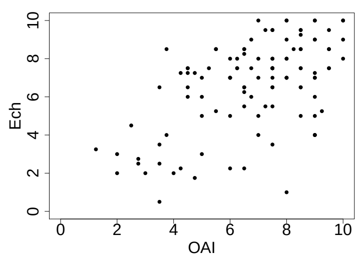
(e) Cl vs. OAI, r =0.62, N =114, p <0.01 (f) War vs OAI, r =0.17, N =115





(g) Tim vs. OAI, r =0.68, N =114, p <0.01 (h) Com vs OAI, ACO: r =0.50, N =115, p <0.01





(i) Ech vs OAI, r =0.31, N =114, p <0.01 (j) Vis vs OAI, r=0.55, N=114, p <0.01

Figure 3.5: Plots of OAI versus other subjective characteristics for ACO tour data. The parameter abbreviations correspond to the scales shown in Figure 3.1.

Table 3.4: The upper portion shows Pearson correlation coefficients, r, between subjective characteristics, for ACO tour. Bold numbers indicate significance at 1% level ($p < 0.01$), underlined significance at 5% level ($p < 0.05$). The lower portion shows number of samples (N).

	OAI	HS	Sup	Ens	Rev	Cl	War	Tim	Com	Ech	Vis
OAI	1	**0.48**	**0.73**	**0.71**	**0.50**	**0.62**	0.17	**0.68**	**0.55**	**0.31**	**0.55**
HS	116	1	**0.42**	**0.54**	0.20	**0.4**	0.08	0.27	**0.32**	**0.37**	0.18
Sup	115	115	1	**0.76**	**0.41**	**0.57**	0.18	**0.67**	**0.49**	0.24	**0.36**
Ens	114	114	114	1	**0.27**	**0.64**	0.12	**0.54**	**0.36**	**0.38**	**0.39**
Rev	115	115	115	114	1	0.15	0.12	**0.42**	**0.34**	0.18	0.26
Cl	114	114	114	113	114	1	-0.09	**0.36**	**0.35**	**0.39**	**0.37**
War	115	115	115	114	115	114	1	**0.43**	-0.03	0.04	0.06
Tim	114	114	114	113	114	113	120	1	**0.46**	0.26	**0.48**
Com	113	113	113	112	113	112	112	112	1	0.18	**0.53**
Ech	114	114	114	113	114	113	113	113	113	1	0.25
VI	114	114	114	113	114	113	112	113	112	113	1

3.3.3 Investigating the impact of position on stage and instrument: ACO

It is interesting to investigate whether the orchestra average is a good indication of the individual player assessments, or whether individual players are affected by other factors, such as location on stage or instrument. Symphony orchestras have commonly been the focus of previous studies of stage acoustics. A symphony orchestra has a far greater number of musicians (i.e. above 80 players), and due to the size of the orchestra will use a larger area on the stage. Therefore acoustic conditions may be quite varied for players depending on their location on the stage. The chamber orchestra investigated in this study consisted of 22 musicians and used a comparatively small area of stage. Based on this it is hypothesised that acoustic conditions were similar for all musicians; although, this will be considered further by examining musician responses based on on-stage location. Similarly, for a symphony orchestra there is a large number of instruments, but in the chamber orchestra studied here most musicians were playing stringed instruments (as well as a smaller number of wind instruments). Due to this it is hypothesised the instrument is a less significant factor for our study.

When examining a whole orchestra average (for OAI) standard deviations (σ) were reasonably low (the highest being $\sigma = 2.34$ for QC, but for other cases $\sigma =$ between 1–2). If position on stage or instrument played impacted the assessment of OAI it is expected that there will be improved agreement within the group. If the sample size for each instrument/position on stage was sufficiently large this could be investigated with a statistical analysis. However, due to the small sample sizes (for example when considering position and instrument there are many groups made up of only two players) this issue will be discussed qualitatively.

The stage was split into four groups (positions 1, 2, 3 and 4), to correspond the locations used for on-stage measurements (see Figure 5.7, Chapter 5). For the ACO tour different stage configuration were used at different times; although commonly the musicians who were considered to be in position 1 were 1st violins, the musicians in position 2 were cello or double bass players, the musicians in position 3 were oboe, horns, bassoon or viola players and the musicians in position 4 were 2nd violins. Some of the participants listed their instrument as 1st violin and 2nd violin, indicating they would have played in both positions 1 and 2 at different times. In Figure 3.6 an example of the stage configuration used during the ACO tour is shown. In Table 3.5 the sample size at each position is given.

The impact of on-stage location on assessments of OAI has been considered. Overall, dividing the musicians into on-stage positions did not improve agreement in auditoria assessments, but this may simply be due to the small number of musicians grouped into each on-stage location, and the fact that some musicians played in multiple locations on stage. Additionally, the on-stage measurements conducted generally showed similar results at different locations on stage, indicating minimal variations in on-stage acoustic conditions for a given auditorium stage (this is discussed later in Chapter 5). Alternatively, a lack of variation in musician ratings around the stage could potentially be caused by musicians talking to one another about their acoustical opinions before or while filling in the surveys.

Assessments for OAI based on instrument were also considered. This qualitative analysis was again made difficult by small sample sizes when considering different instruments, see Table 3.6. Although the sample size for violins was larger since 6 out of 15 respondents were violin players (either 1st or 2nd violin). For this case cello, 1st violins, and viola showed no improvement in agreement (all with sample size of only 2 players). However, oboe and horn perhaps showed some improved agreement (again each group with a sample size of 2 players). Overall, from the data collected in this study it is difficult to comment on whether instrument impacted ratings of OAI.

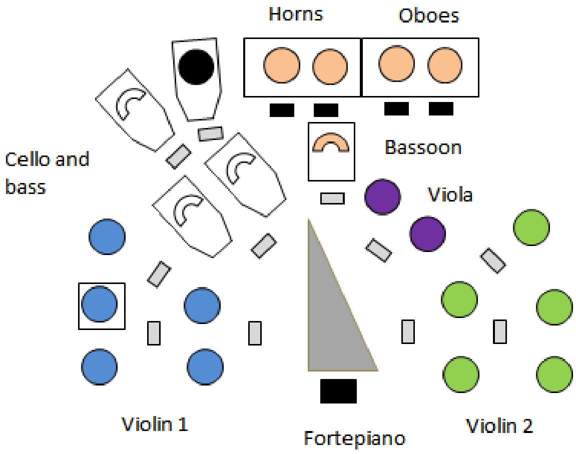


Figure 3.6: An example of the stage configuration used for the ACO tour, image courtesy of the Australian Chamber Orchestra.

Table 3.5: Sample size for on-stage positions for ACO data

Group	Sample size
Orchestra total	15
Position 1	2
Position 2	3
Position 3	6
Position 4	0
Multiple positions	4

Table 3.6: Sample size for instrument groups for ACO data

Group	Sample size
Orchestra total	15
1^{st} Violin	2
Violin (1^{st} or 2^{nd})	6
Viola	2
Cello	2
Oboe	2
Horn	2

3.4 Survey results with ACO2

For the ACO2 tour 15 out of a possible 17 musician completed the questionnaire (88% response rate). In the case of ACO2 each auditorium has been given identifier based on an abbreviation of the name of the town the hall was located in; the actual performing spaces were Bellingen Memorial Hall (BEL), the Auditorium at Redland Performing Arts Centre, Cleveland (CLE), St John's School Hall, Mullumbimby (MUL), Armidale Town Hall (ARM), Moncrieff Theatre, Bundaberg (BUN), Gold Coast Arts Centre (GOL), Gladstone Entertainment Centre (GLA) and Nambour Civic Centre (NAM). Note that for the Gold Coast and Gladstone venues were conference rooms (with tables and chairs) rather than auditoria designed for music.

Included in the respondents from ACO2 were eight violins, three violas, three cellos and one double bass player.

Figure 3.7 shows the mean orchestra assessment (and corresponding standard deviation) for OAI for the ACO2 tour data. In Figures 3.8a and 3.8b the mean and median results for subjective characteristics for ACO2 are presented. The most preferred hall was BEL, which was rated well across all the subjective characteristics. In terms of order of preference, there was no difference between the orchestra mean and median. NAM was clearly the least preferred hall. The written comments from musicians are included in Table 3.7.

3.4.1 Difference between subjective characteristics in different auditoria: ACO2

This section considers which of the auditoria are judged as being significantly different in terms of OAI, based on assessments from the whole orchestra for ACO2, in the same manner as was conducted for the ACO data set in Section 3.3.1. Post hoc testing was conducted, and p values corrected with a Holm correction. The Levene Test was also conducted, and confirmed homogeneity of variance was met. Table 3.8 summarises the p values for differences between orchestra assessments of OAI in auditoria for the ACO2 data. BEL is rated significantly above all auditoria in the study, except CLE and MUL (at either a 1% or 5% level). NAM is rated significantly below all auditoria in the study, except GOL and GLA (at either a 1% or 5% level). Similarly, GLA is rated significantly below all the above auditoria

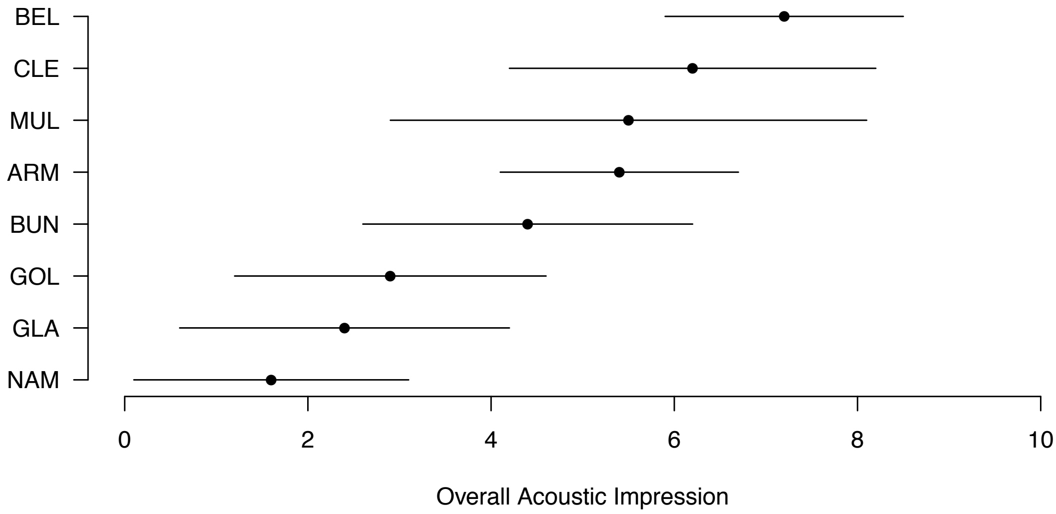
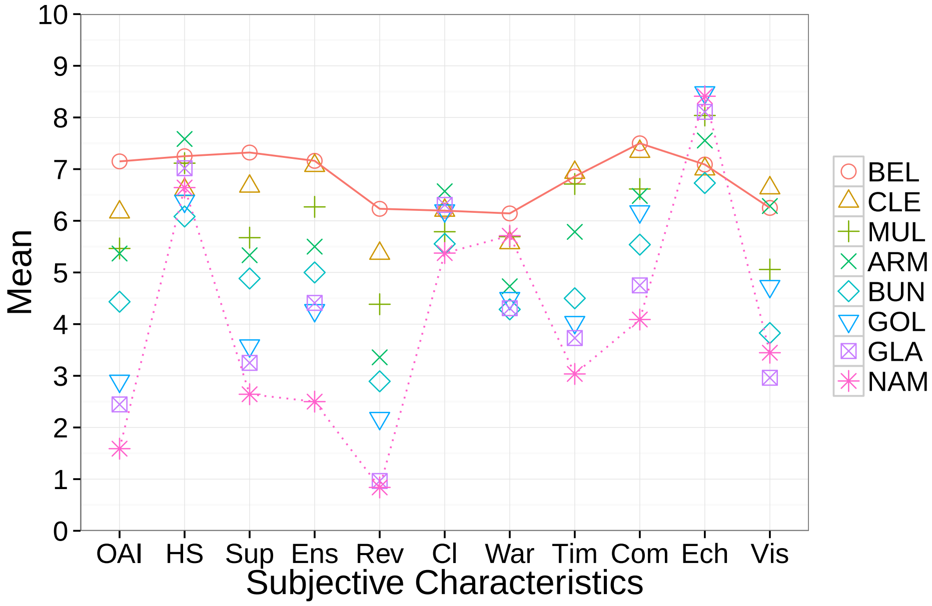


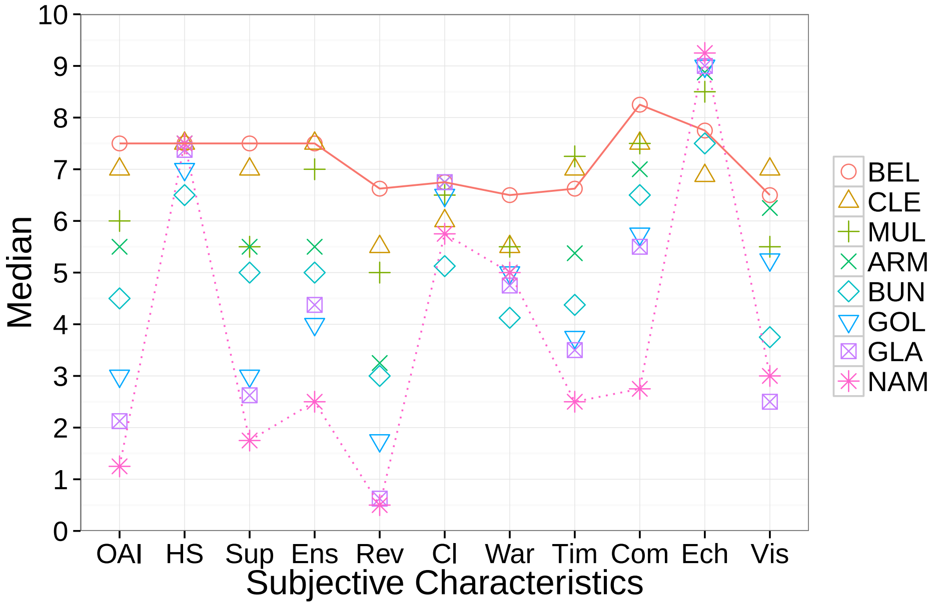
Figure 3.7: Mean and standard deviation for 'Overall Acoustic Impression' in each auditorium for ACO2

Table 3.7: Comments from musicians regarding on-stage acoustics in auditoria for ACO2 tour

Auditoria	Comments
BEL	'Good hall, but we didn't use stage, played in hall'
	'Acoustic good, not too dry'
CLE	'Very very loud on stage'
	'Good venue, light and stage space sufficient for orchestra'
	'Probably the nicest acoustic of this regional tour'
MUL	'Stage too high'
ARM	'Stage was a bit small so setup was not perfect, so visual lines to each other weren't perfect'
	'Good hall, but not special'
	'Stage a bit small for setup of orchestra. Lighting difficulties'
GOL	*no comments*
BUN	*no comments*
GLA	'Doesn't feel like concert hall'
	'Good amount of room on stage. Bit too dry acoustic wise.'
	'Air conditioning noise interfered with ability to hear instruments properly. Light too distracting (multi-coloured)'
NAM	'Big stage'
	'Dynamic contrast extremely difficult to attain'
	'Sound doesn't project at all'
	'Not very pleasant venue for the performer - too dry.'



(a) Average orchestra assessments for subjective characteristics in auditoria, for ACO2. A solid line is shown through the data for the highest rated auditorium (BEL) and a dashed line through the data for the lowest rated auditorium (NAM).



(b) Median orchestra assessments for subjective characteristics in auditoria, for ACO2. A solid line is shown through the data for the highest rated auditorium (BEL) and a dashed line through the data for the lowest rated auditorium (NAM).

Figure 3.8: Average and median for subjective characteristics for ACO2

Table 3.8: p values (adjusted with Holm) for difference between orchestra assessments of OAI in auditoria assessed by ACO2. Bold numbers indicate significance at 1% level ($p < 0.01$), underlined significance at 5% level ($p < 0.05$).

	BEL	CLE	MUL	ARM	BUN	GOL	GLA
CLE	0.513						
MUL	0.363	1					
ARM	<u>0.026</u>	1	1				
BUN	<u>0.019</u>	0.284	1	0.879			
GOL	**0.000**	**0.001**	0.271	<u>0.010</u>	0.289		
GLA	**0.000**	<u>0.014</u>	<u>0.011</u>	**0.003**	<u>0.019</u>	1	
NAM	**0.000**	**0.001**	<u>0.019</u>	**0.000**	**0.004**	0.765	1

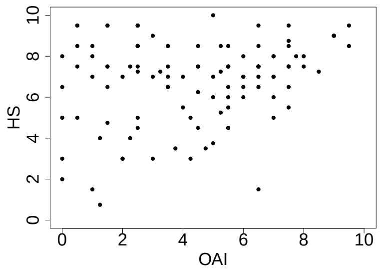
in the study, with the exception of GOL (at either a 1% or 5% level). For the intermediate auditoria some differences, but not all, are significant.

3.4.2 Subjective characteristics in relation to OAI: ACO2

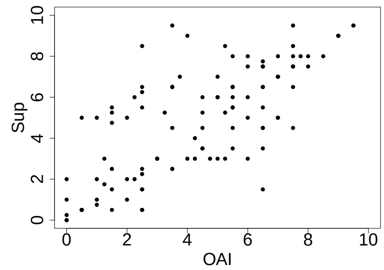
Subjective data scales and OAI have been plotted against each other, in the same manner as previously for ACO, as shown in Figure 3.9. Also, a correlation matrix has been produced to examine relationships between OAI and the other subjective scales, as well as any relationships between all the other subjective scales, as shown in Table 3.9. The most highly correlated attributes with OAI were: 'reverberance', 'support', 'ensemble' and 'timbre' (r between 0.68–0.75). These results, in comparison to the other musician survey results, are discussed in Section 3.7.

3.4.3 Investigating the impact of position on stage and instrument: ACO2

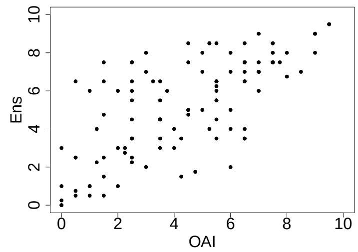
The stage plan for ACO2 tour is shown in Figure 3.10. Violas are in position 3, and cellos and double basses are in position 4. 1$^{\text{st}}$ and 2$^{\text{nd}}$ violins are in positions 1 and 2; which have been analysed together as most players specified that they played both 1$^{\text{st}}$ and 2$^{\text{nd}}$ violin (i.e. they played in both positions 1 and 2). The sample size for each on-stage position for ACO2 is provided in Table 3.10. Overall, dividing the musicians in on-stage position did not improve agreement in assessments. Clear improvement in agreement with position is made



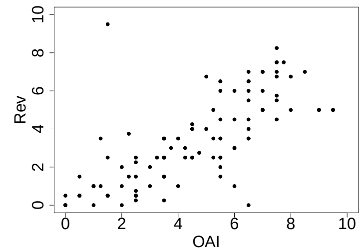
(a) HS vs. OAI, r =0.24, N =115, p <0.05



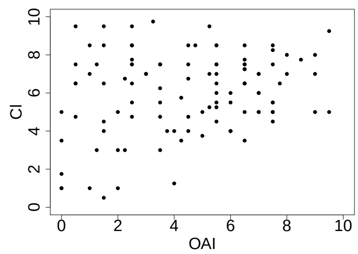
(b) Sup vs. OAI, r =0.73, N =115, p <0.01



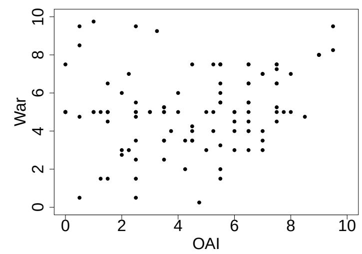
(c) Ens vs. OAI, r =0.70, N =114, p <0.01



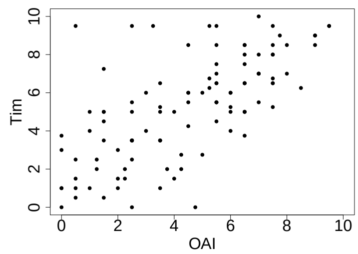
(d) Rev vs. OAI, r =0.75, N =112, p <0.01



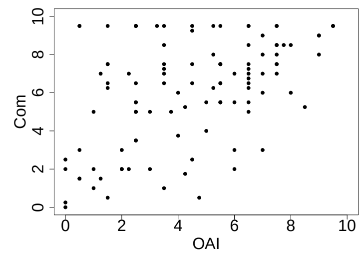
(e) Cl vs. OAI, r =0.23, N =111, p <0.05



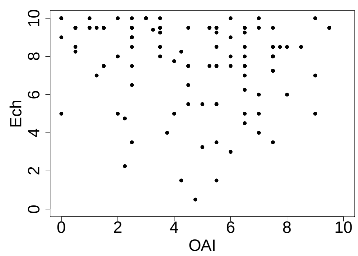
(f) War vs OAI, r =0.22, N =108, p <0.05



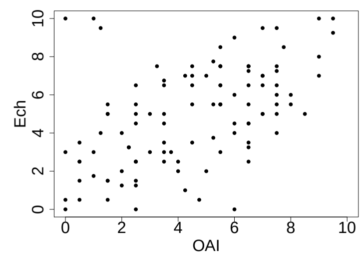
(g) Tim vs. OAI, r =0.68, N =111, p <0.05



(h) Com vs OAI, r =0.47, N =108, p <0.01



(i) Ech vs OAI, r =-0.17, N =109



(j) Vis vs OAI, r=0.52, N=110, p <0.01

Figure 3.9: Plots of OAI versus other subjective characteristics for ACO2 tour data. The parameter abbreviations correspond to the scales shown in Figure 3.1.

Table 3.9: The upper portion shows Pearson correlation coefficients, r, between subjective characteristics, for ACO2 tour. Bold numbers indicate significance at 1% level ($p < 0.01$), underlined significance at 5% level ($p < 0.05$). The lower portion shows number of samples (N).

	OAI	HS	Sup	Ens	Rev	Cl	War	Tim	Com	Ech	Vis
OAI	1	<u>0.24</u>	**0.73**	**0.70**	**0.75**	<u>0.23</u>	<u>0.22</u>	**0.68**	**0.47**	-0.17	**0.52**
HS	115	1	<u>0.22</u>	**0.34**	0.14	**0.38**	**0.33**	**0.34**	**0.36**	<u>0.19</u>	0.03
Sup	115	115	1	**0.64**	**0.63**	0.11	<u>0.22</u>	**0.52**	**0.37**	-0.15	**0.37**
Ens	114	114	114	1	**0.5**	**0.45**	0.13	**0.66**	**0.53**	0.04	**0.44**
Rev	112	112	112	112	1	0.05	<u>0.21</u>	**0.56**	**0.44**	**-0.27**	**0.41**
Cl	111	111	111	111	111	1	0.04	**0.34**	**0.31**	<u>0.24</u>	0.13
War	108	108	108	108	108	108	1	**0.47**	**0.28**	0.03	**0.22**
Tim	111	111	111	111	111	111	108	1	**0.68**	0.08	**0.52**
Com	108	108	108	108	108	108	105	108	1	0.09	**0.44**
Ech	109	109	109	109	109	109	106	109	108	1	0.09
VI	110	110	110	110	110	110	110	107	108	109	1

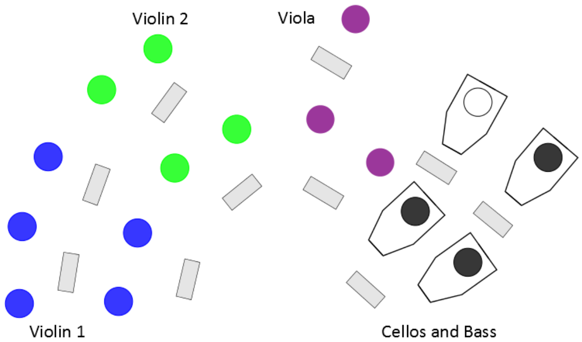


Figure 3.10: The stage configuration used for the ACO2 tour, image courtesy of the Australian Chamber Orchestra.

unlikely by the small size of on-stage position group, and the fact the orchestra would use a relatively small area of stage. Similarly, the sample size for each instrument for ACO2 is provided in Table 3.11, and again improved agreement did not occur with instrument. This is excepted as in this case grouping the musicians by either instrument played or by on-stage position is essentially the same.

Table 3.10: Sample size for on-stage positions for ACO2 data

Group	Sample size
Orchestra total	15
Position 1 and 2	8
Position 3	3
Position 4	4
Multiple positions	4

Table 3.11: Sample size for instrument groups for ACO2 data

Group	Sample size
Orchestra total	15
Violin (1st or 2nd)	8
Viola	3
Cello	3
Double Bass	1

3.5 Survey results with ACO Collective

For the ACO Collective tour, 9 out of a possible 17 musician completed the questionnaire (53% response rate). In the case of ACO Collective each auditorium has been given an identifier based on an abbreviation of the name of the town the hall was located in; the actual performing spaces were Dubbo Regional Theatre (DUB), The Capitol Theatre, Tamworth (TAM), Griffith Regional Theatre (GRI), Manning Entertainment Centre, Taree (TAR), Wagga Wagga Civic Centre (WAG), Albury Entertainment Centre (ALB), and Q Theatre, Penrith (PEN).

Included in the respondents from ACO Collective were six violins, one viola and two cellos.

Figure 3.11 shows the mean orchestra assessment (and corresponding standard deviation) for OAI for the ACO Collective tour data. In Figures 3.12a and 3.12b the mean and median results for subjective characteristics for ACO Collective are presented. The written comments from musicians are included in Table 3.12.

In this case the difference between auditoria in the study, based on OAI are analysed as well as the relationship between OAI and other subjective characteristics. Due to the small sample size for this tour trends based on instrument and position on stage have not been examined. However, the stage plan for ACO Collective tour is shown in Figure 3.13.

Table 3.12: Comments from musicians regarding on-stage acoustics in auditoria for ACO Collective tour

Auditorium	Comments
DUB	‘Best acoustic, a very pleasant aura of ‘liveness’ (if a small one)’
TAM	‘Seems to be used a movie theatre as well’
	‘Relatively supportive space - although felt a little thin/exposed. A bit more lively would be preferable for string players.’
GRI	‘Added a positive contribution (if small) to the sound we produced.’
TAR	‘Surprisingly pleasant space to play in (considering it looks like a drama theatre).’
WAG	‘Beautiful space. Just a little more reverb would be preferable (is more reassuring to string players)’
ALB	‘Very unflattering’
	‘Very very dry and doesn’t particularly help performers feel like they’re giving a good performance’
PEN	‘Very very dry - quite a struggle as string players (we felt very exposed)’

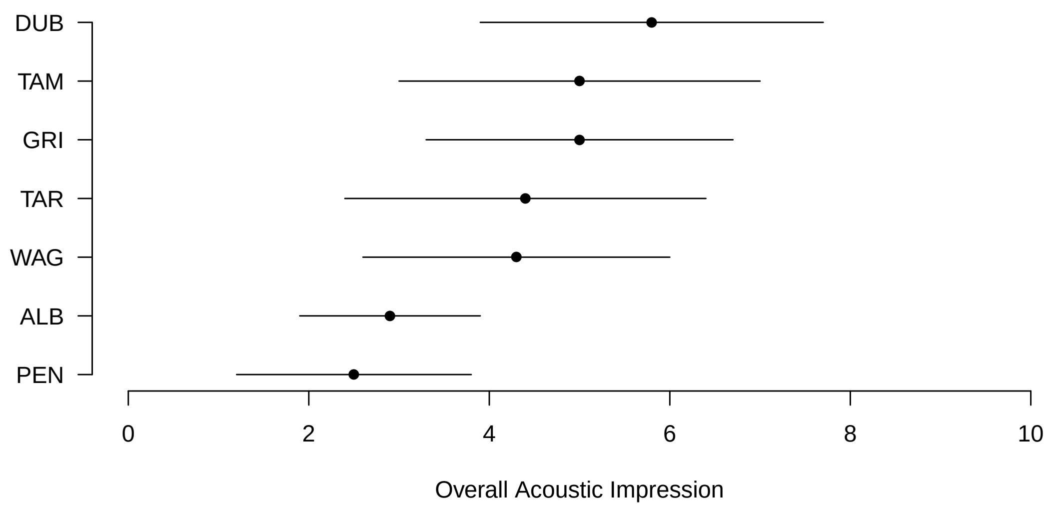
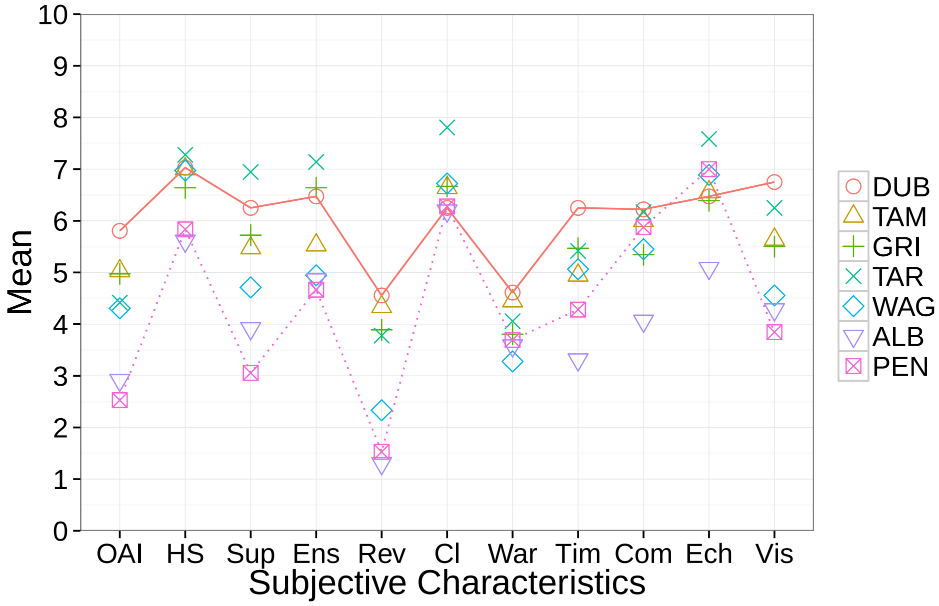
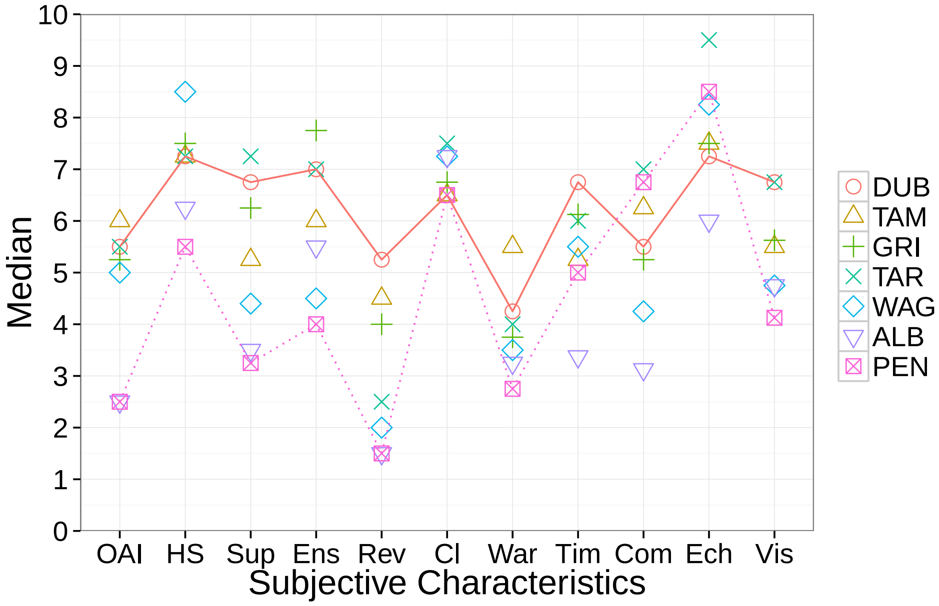


Figure 3.11: Mean and standard deviation for ‘Overall Acoustic Impression’ in each auditorium for ACO Collective



(a) Average orchestra assessments for subjective characteristics in auditoria, for ACO Collective. A solid line is shown through the data for the highest rated auditorium (DUB) and a dashed line through the data for the lowest rated auditorium (PEN).



(b) Median orchestra assessments for subjective characteristics in auditoria, for ACO Collective. A solid line is shown through the data for the highest rated auditorium (DUB) and a dashed line through the data for the lowest rated auditorium (PEN).

Figure 3.12: Average and median for subjective characteristics for ACO Collective

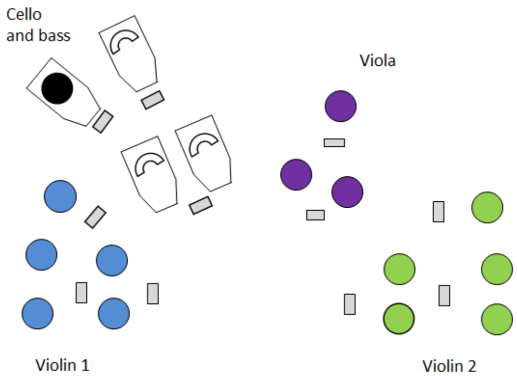


Figure 3.13: The stage configuration used for the ACO Collective tour, image courtesy of the Australian Chamber Orchestra.

Table 3.13: p values (adjusted with Holm) for difference between orchestra assessments of OAI in auditoria assessed by ACO Collective. Underlined numbers indicate significance at 5% level ($p < 0.05$).

	DUB	TAM	GRI	TAR	WAG	ALB
TAM	1					
GRI	1	1				
TAR	0.897	1	1			
WAG	0.168	1	1	1		
ALB	0.196	0.811	0.359	0.879	0.289	0.977
PEN	<u>0.029</u>	0.088	0.055	0.811	0.168	1

3.5.1 Difference between subjective characteristics in different auditoria: ACO Collective

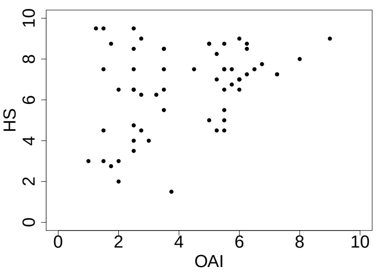
This section considers which of the auditoria are judged as being significantly different in terms of OAI, based on assessments from the whole orchestra for ACO Collective, in the same manner as was conducted for the ACO data set in Section 3.3.1. Post hoc testing was conducted, and p values corrected with a Holm correction. The Levene Test was also conducted, and confirmed homogeneity of variance was met. Table 3.13 summarises the p values for differences between orchestra assessments of OAI in auditoria for the ACO Collective data. In this case only DUB and PEN were found to be significantly different (at the 5% level). There were only 9 respondents in this dataset, and the small sample size may be part of the reason for non-significant differences in terms of OAI.

Table 3.14: The upper portion shows Pearson correlation coefficients, r, between subjective characteristics, for ACO Collective tour. Bold numbers indicate significance at 1% level ($p < 0.01$), underlined significance at 5% level ($p < 0.05$). The lower portion shows number of samples (N).

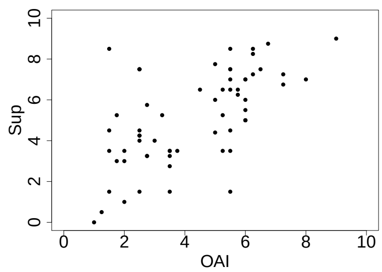
	OAI	HS	Sup	Ens	Rev	Cl	War	Tim	Com	Ech	Vis
OAI	1	0.35	**0.60**	**0.52**	**0.76**	0.03	<u>0.43</u>	<u>0.45</u>	0.14	0.17	**0.51**
HS	62	1	0.39	**0.54**	0.16	0.32	0.12	0.03	<u>0.46</u>	**0.65**	0.17
Sup	63	62	1	**0.68**	**0.60**	0.15	0.26	<u>0.42</u>	0.19	0.16	**0.47**
Ens	63	62	63	1	0.41	0.26	0.24	0.28	0.38	<u>0.40</u>	0.26
Rev	63	62	63	63	1	-0.04	**0.55**	**0.62**	0.17	0.07	**0.62**
Cl	63	62	63	63	63	1	-0.06	0.16	0.37	0.34	0.24
War	63	62	63	63	63	63	1	**0.47**	0.13	0.15	**0.44**
Tim	59	58	59	59	59	59	59	1	0.17	0.12	**0.55**
Com	59	58	59	59	59	59	59	59	1	<u>0.41</u>	0.21
Ech	63	62	63	63	63	63	63	59	59	1	0.18
VI	60	59	60	60	60	60	60	59	59	60	1

3.5.2 Subjective characteristics in relation to OAI: ACO Collective

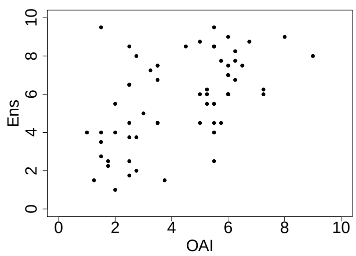
Subjective data scales and OAI have been plotted against each other, in the same manner as previously for ACO, as shown in Figure 3.14. Also, a correlation matrix has been produced to examine relationships between OAI and the other subjective scales, as well as any relationships between all the other subjective scales, as shown in Table 3.14. The most highly correlated attributed with OAI were: 'reverberance', 'support', 'ensemble' and 'visual impression' (r between 0.51–0.76). These results, in comparison to the other musician survey results, are discussed in Section 3.7.



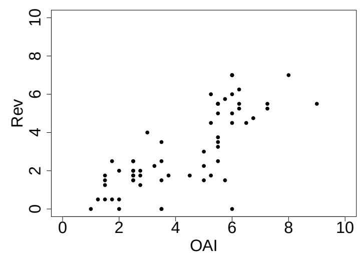
(a) HS vs. OAI, r =0.35, N =62



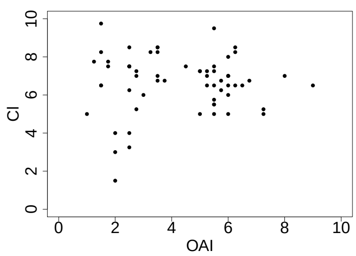
(b) Sup vs. OAI, r =0.60, N =63, p <0.01



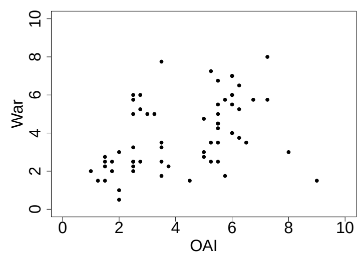
(c) Ens vs. OAI, r =0.53, N =63, p <0.01



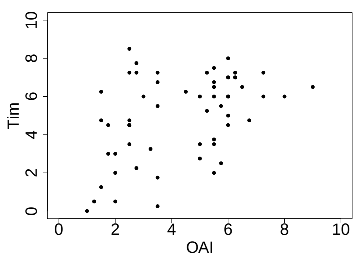
(d) Rev vs OAI, r =0.76, N =63, p <0.01



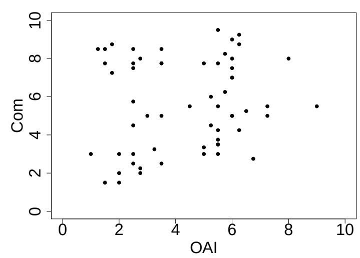
(e) Cl vs. OAI, r =0.03, N =63



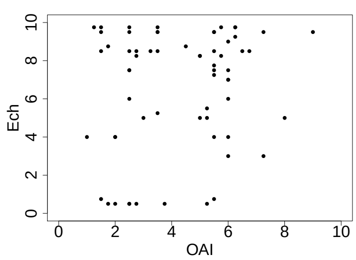
(f) War vs. OAI, r =0.43, N =63, p <0.05



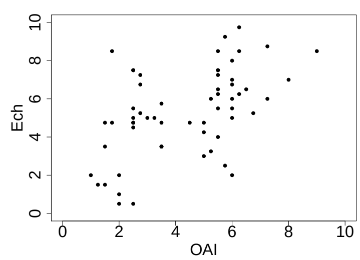
(g) Tim vs. OAI, r =0.45, N =59, p <0.05



(h) Com vs. OAI, ACO: r =0.14, N =59



(i) Ech vs. OAI, r =0.17, N =63



(j) Vis vs. OAI, r =0.51, N =60, p <0.01

Figure 3.14: Plots of OAI versus other subjective characteristics for ACO Collective tour data. The parameter abbreviations correspond to the scales shown in Figure 3.1.

3.6 Principal component analysis: ACO and ACO2

Principal component analysis (PCA) is a statistical technique which can be used to reduce the dimensionality of a set of data [Jolliffe, 2002]. This is advantageous in a large dataset with numerous variables, such as the chamber orchestra datasets in this study (each dataset contains 11 subjective attributes).

In Sections 3.3.2 and 3.4.2 correlations between 'overall acoustic impression' (OAI) and other subjective attributes were explored for ACO and ACO2 respectively. As an extension to this PCA is now conducted to examine whether the subjective attributes included on the questionnaire can be condensed into a few number of underlying variables (or principal components).

In this section PCA is conducted for ACO, as well as for ACO2, and finally for the two datasets pooled. ACO and ACO2 datasets are used because in both cases the response rate from the chamber orchestras was high, ensuring a large sample size. The response rate from ACO Collective was lower, and this dataset has not been included in PCA.

When conducting PCA, overall acoustic impression (OAI) has been removed from the orchestra datasets. OAI was removed because it is effectively the musicians' rating on all the other acoustic attributes, and excluding OAI from PCA allows an exploration of which of the other subjective attributes are related. One consideration when conducting PCA is whether to include the scale Rev, since this scale is set up with an optimum point at 5 (out of 10), whereas the other scales on the questionnaire have the optimum point at 10. However, Rev has been included (without any alterations made to the scale) so that relationship between Rev and subjective characteristics can be observed.

3.6.1 ACO dataset

PCA was conducted on the ACO dataset, with OAI removed. The first principal component accounts for 42% of the total variance, and consideration of the first three principal components accounts for 66 % of the total variance. A scree plot showing all the principal components in Figure 3.15 demonstrates this visually. The first three principal components will be considered further.

Table 3.15: Correlation between original variables and principal components for ACO dataset, with correlations above 0.3 shown in bold.

	PC1	PC2	PC3
HS	−0.29	0.24	**−0.33**
Sup	**−0.41**	−0.07	−0.06
Ens	**−0.41**	0.14	−0.22
Rev	−0.25	−0.28	0.23
Cl	**−0.34**	**0.38**	−0.08
War	−0.09	**−0.68**	**−0.46**
Tim	**−0.38**	**−0.39**	−0.02
Com	**−0.32**	−0.01	**0.50**
Ech	−0.24	0.28	**−0.30**
Vis	**−0.30**	−0.05	**0.47**

The correlations between the original attributes and the first three principal components are summarised in Table 3.15. Overall PC1 appears to be a very general factor which correlates somewhat with almost all the subjective attributes included on the survey (including Vis), with the exception of War. Principal component 2 (PC2) correlates strongly with War. From PC2, there also appears to be an inverse relationship between Cl/Ech/HS and Rev/Tim/War. Principal Component 3 (PC3) correlates most highly with Vis, as well as with Com, and inversely with War.

A biplot of PC1 and PC2 is shown in Figure 3.16 and a biplot of PC1 and PC3 is shown in Figure 3.17. In the biplots each data point corresponds to a single questionnaire from a musician. Figure 3.16 shows that most variables are grouped together, which indicates they are all correlated, whereas War is notably separated from the other attributes. Although, Rev and Tim are somewhat closer to PC2 than the other attributes, indicating it is somewhat correlated with War and somewhat correlated with all the other attributes. Figure 3.16 again shows most variables contributing to PC1, although Com and Vis contribute to both PC1 and PC3.

3.6.2 ACO2 dataset

PCA was conducted on the ACO2 dataset, with OAI removed. The first principal component accounts for 40% of the total variance, and considering the first three principal components accounts for 66 % of the total variance. A scree plot showing all the principal components

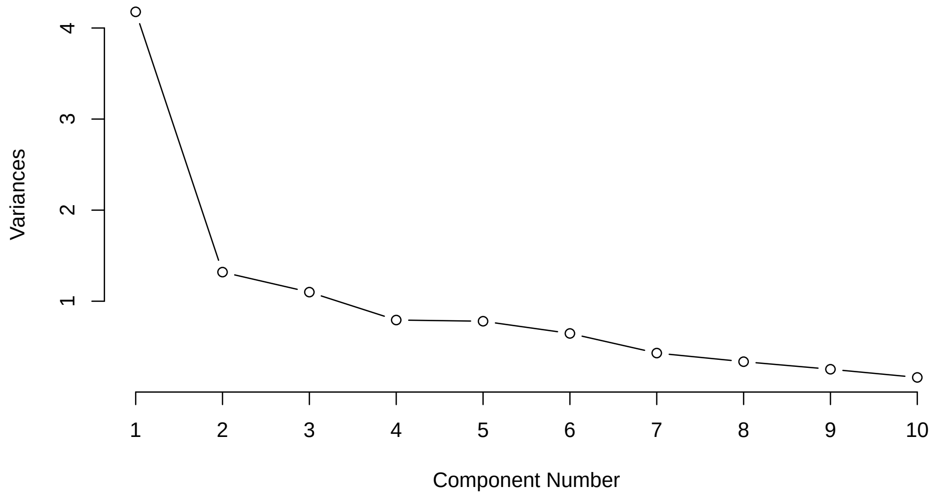


Figure 3.15: Scree showing the principal components for ACO data.

in Figure 3.15 demonstrates this visually. As for the ACO dataset, the first three principal components will be considered further.

Table 3.16: Correlation between original variables and principal components for ACO2 dataset, with correlations above 0.3 shown in bold.

	PC1	PC2	PC3
HS	−0.23	**−0.42**	**0.34**
Sup	**−0.36**	0.29	−0.08
Ens	**−0.40**	−0.03	**−0.33**
Rev	**−0.34**	**0.41**	−0.01
Cl	−0.22	**−0.48**	**−0.31**
War	−0.23	−0.03	**0.78**
Tim	**−0.44**	−0.02	0.10
Com	**−0.38**	−0.09	0.00
Ech	−0.05	**−0.56**	−0.12
Vis	**−0.31**	0.16	−0.20

The correlations between the original attributes and the first three principal components are summarised in Table 3.16. Principal Component 1 (PC1) correlates at least somewhat with all subjective attributes, except Ech. Principal component 2 (PC2) correlates strongly with Ech/Cl/HS, and inversely with Rev/Sup. Principal Component 3 (PC3) correlates most strongly with War.

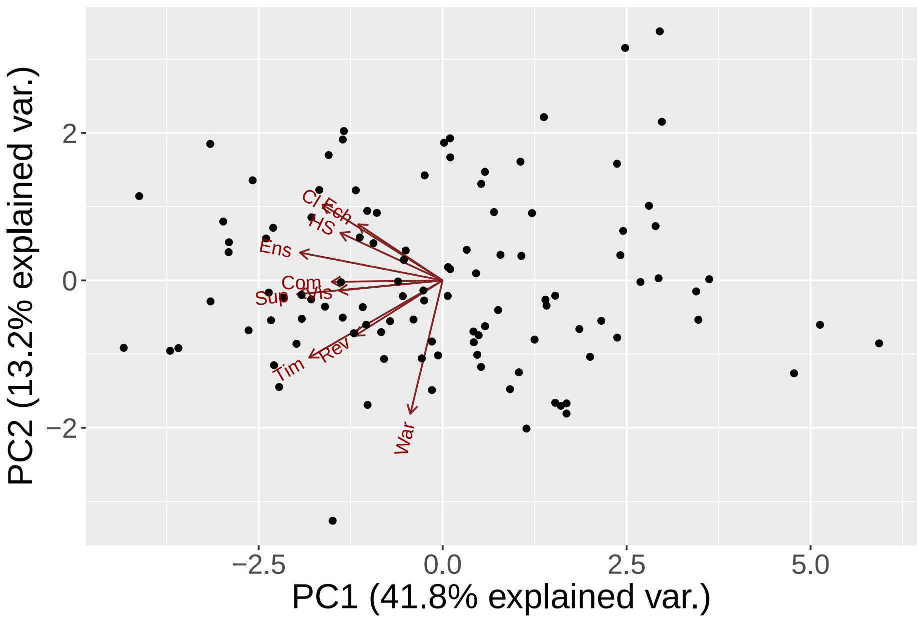


Figure 3.16: Biplot showing PC1 and PC2 for ACO data.

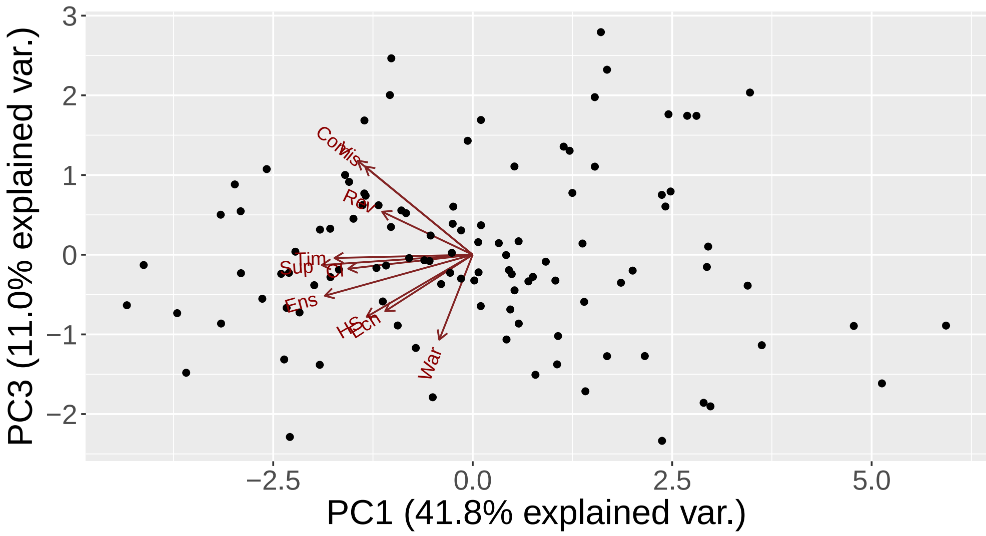


Figure 3.17: Biplot showing PC1 and PC3 for ACO data.

A biplot of the first two principal components is shown in Figure 3.19, showing that Ech is strongly contributing to PC2 (as well as HS/Cl) with an inverse contribution to PC2 from Rev/Sup. Additionally, a biplot of PC1 and PC3 is shown in is shown in Figure 3.20, and shows that War is the attribute most correlated with PC3.

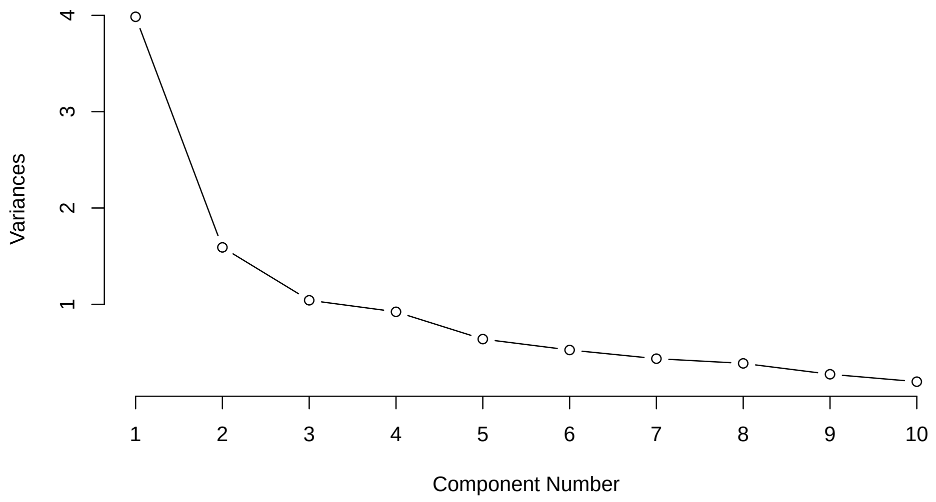


Figure 3.18: Scree showing the principal components for ACO2 data.

3.6.3 ACO and ACO2 datasets pooled

Finally, PCA was conducted on the ACO and ACO2 datasets pooled, again OAI removed. The first principal component accounts for 41% of the total variance, and consideration of the first three principal components accounts for 67 % of the total variance. A scree plot showing all the principal components in Figure 3.21 demonstrates this visually. The first three principal components will be considered further.

Table 3.17: The first three principal components for ACO and ACO2 datasets pooled, with correlations above 0.3 shown in bold.

	PC1	PC2	PC3
HS	−0.26	**0.36**	−0.29
Sup	**−0.39**	−0.13	0.11
Ens	**−0.40**	0.15	0.14
Rev	**−0.32**	**−0.40**	0.14
Cl	−0.26	**0.48**	0.19
War	−0.17	−0.23	**−0.83**
Tim	**−0.42**	−0.14	−0.17
Com	**−0.35**	0.01	0.12
Ech	−0.09	**0.58**	−0.20
Vis	**−0.33**	−0.17	0.22

The correlations between the original attributes and the first three principal components

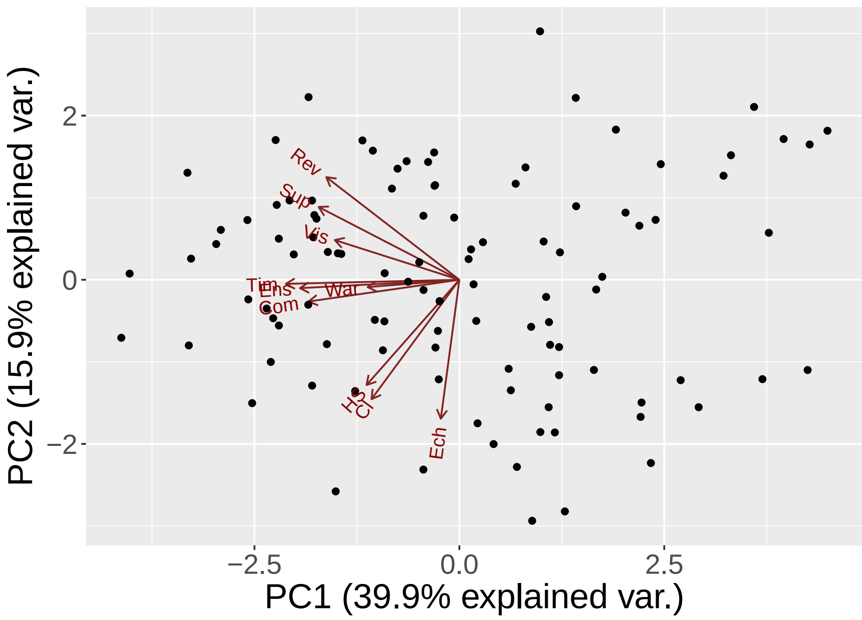


Figure 3.19: Biplot showing PC1 and PC2 for ACO2 data.

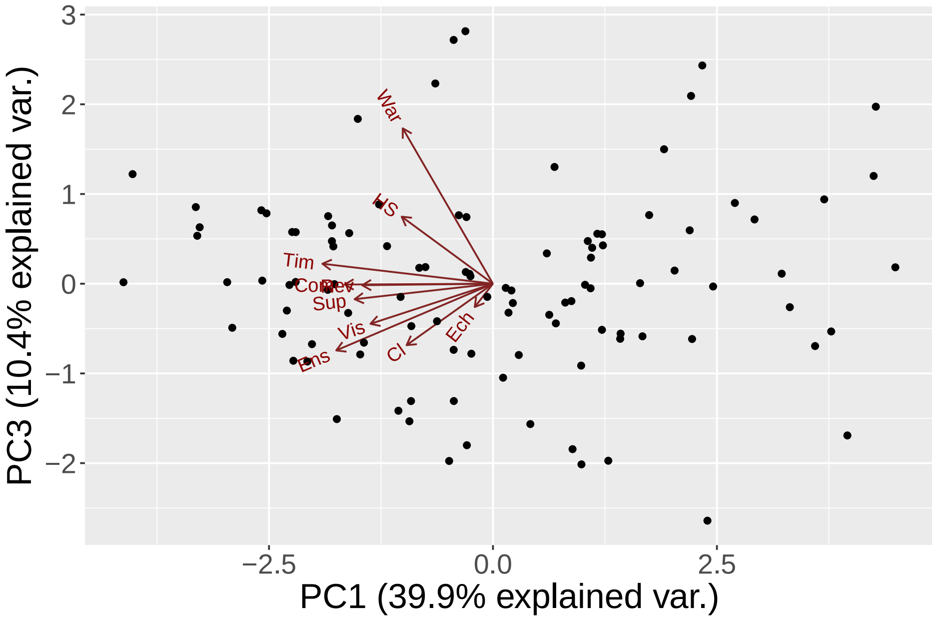


Figure 3.20: Biplot showing PC1 and PC3 for ACO2 data.

are summarised in Table 3.17. Now that ACO and ACO2 datasets are combined neither War nor Ech correlate particularly well with PC1. A biplot of PC1 and PC2 is shown in Figure 3.22. This shows most of the subjective attributes relate to PC1, except Ech (and to some extent HS/Cl), which contribute to PC2. Rev/War also contribute to PC2, but in an inverse manner to Ech/HS/Cl. A biplot of PC1 and PC3 is shown in Figure 3.23, which shows War contributes most to PC3.

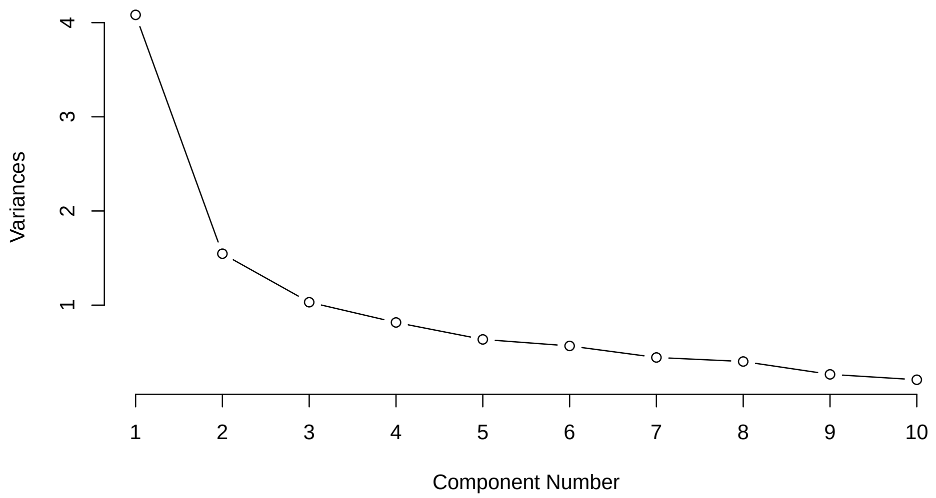


Figure 3.21: Scree showing the principal components for ACO and ACO2 datasets pooled.

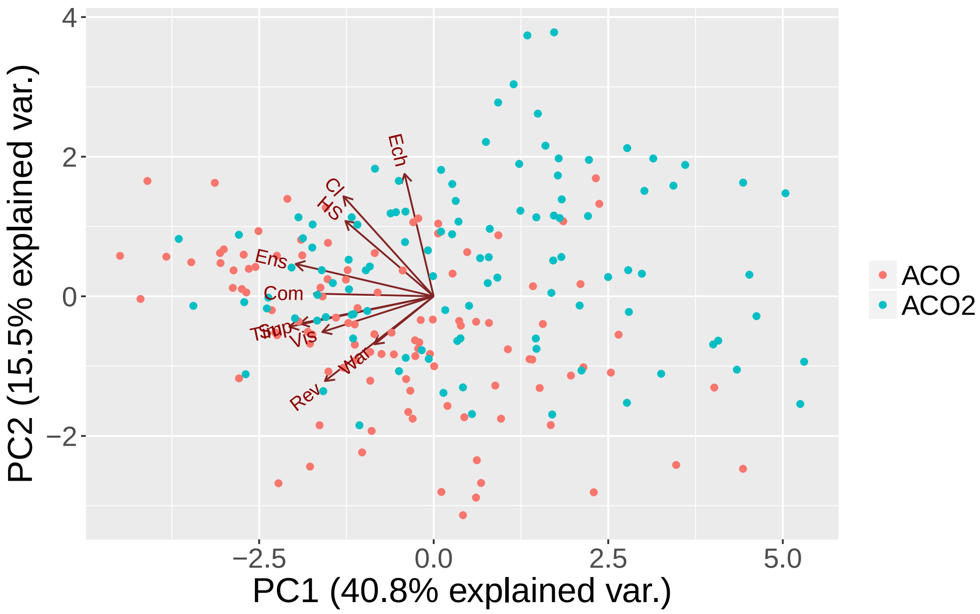


Figure 3.22: Biplot showing PC1 and PC2 for ACO and ACO2 datasets pooled.

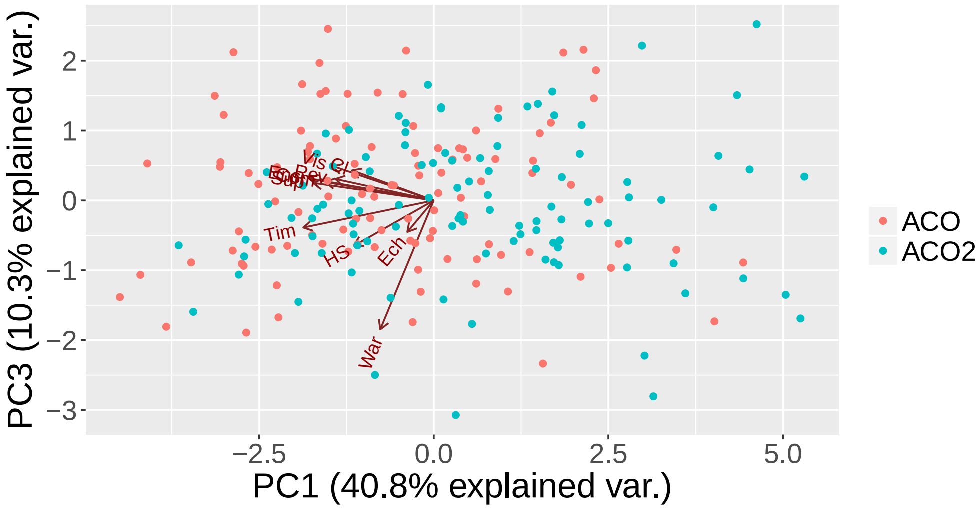


Figure 3.23: Biplot showing PC1 and PC3 for ACO and ACO2 datasets pooled.

3.7 Discussion

During the surveying schedule, the ACO performed in prominent purpose-built Australian auditoria, whereas ACO2 and ACO Collective performed in regional venues including multi-purpose halls and even conference spaces. The ACO is an internationally renowned chamber orchestra with highly experienced professional musicians, whereas ACO2/ACO Collective feature professional musicians as well as young professional musicians with less experience. Interestingly, in spite of these differences, there were remarkable similarities between ACO, ACO2, and ACO Collective in the ranking of subjective attributes that were well-correlated with overall acoustic impression. However, there was also some notable differences between the datasets which can be considered further.

The results for correlation between OAI and other attributes for the three chamber orchestras surveyed are summarised in Table 3.18. Only two attributes of significance differed markedly between ACO and ACO2 and ACO Collective in terms of both ranking and correlation coefficient. These were 'Reverberance' (ranked 7th out of 10 attributes by ACO, but ranked 1st out of 10 attributes by both ACO2 and ACO Collective), and 'Clarity' (ranked 4th out of 10 attributes by ACO, but ranked 8th and 10th for ACO2 and ACO Collective respectively). The correlation coefficients for 'Reverberance' were r = 0.50, 0.75, 0.76 for ACO/ACO2/ACO Collective respectively, and for 'Clarity' were r = 0.62, 0.23, 0.03. With these two attributes removed from the list, the top attributes were remarkably similar, being in order 'Support' (r = 0.73/0.73/0.60 for ACO/ACO2/ACO Collective respectively), 'Ensemble' (r = 0.71/0.70/0.52), 'Timbre' (r = 0.68/0.68/0.45) and 'Visual Impression' (r = 0.55/0.52/51) which were all significant at the 1% level. They were not only ranked in the same order, but in most cases had similar correlation coefficients. ACO Collective correlation coefficients were in general slightly lower, however noting the response rate was lower for this dataset. The remaining attributes were also ranked similarly but were in some cases significant only at the 5% level or not at all: 'Communication with the main auditorium' (r = 0.55/0.47/0.14), 'Hearing Self' (r = 0.48/0.24/35), 'Echoes' (r =0.31/-0.17/0.17) and 'Warmth' (r = 0.17/0.22/0.43). The sample size for ACO and ACO2 datasets were in the range N =108–116, depending slightly on whether musicians left any scales blank on questionnaires. In the case of ACO Collective the sample size was slightly lower, because there was fewer participants (9 respondents from ACO Collective compared to 15 respondents from ACO and 15 respondents ACO2) and the tour included one less auditorium. The sample size for ACO Collective dataset was been N=59–63. The importance of 'Support', 'Ensemble'

Table 3.18: A summary of ranking of attributes in terms of correlation with OAI and correlation coefficients (r) with OAI for the three chamber orchestras surveyed. Significance at a 1% level is shown in bold, and at a 5% level is underlined.

	Ranking			Correlation coefficient (r) with OAI		
Attribute	ACO	ACO2	ACO Collective	ACO	ACO2	ACO Collective
Sup	1	2	2	**0.73**	**0.73**	**0.60**
Ens	2	3	3	**0.71**	**0.70**	**0.52**
Tim	3	4	5	**0.68**	**0.68**	<u>0.45</u>
Cl	4	8	10	**0.62**	<u>0.23</u>	0.03
Com	5	6	9	**0.55**	**0.47**	0.14
Vis	6	5	4	**0.55**	**0.52**	**0.51**
Rev	7	1	1	**0.50**	**0.75**	**0.76**
HS	8	7	7	**0.48**	<u>0.24</u>	0.35
Ech	9	10	8	**0.31**	−0.17	0.17
War	10	9	6	0.10	<u>0.22</u>	<u>0.43</u>

and ‘Timbre’ to chamber orchestra musicians is apparent from the high correlation between these aspects and OAI in the datasets. Sanders [2003] found ‘Support’ and ‘Ensemble’ to be key subjective characteristics in a study of chamber ensemble musicians but did not ask musicians to rate auditoria in regard to ‘Timbre’.

‘Reverberance’ is known to be a subjectively important characteristic for musicians playing on stage; in this study it was highly correlated with OAI for ACO2 and ACO Collective, but not as highly correlated for ACO. This is likely to be because the ‘Reverberance’ was near the optimum of 5 in all auditoria in the ACO playing tour because all auditoria were purpose-built concert halls (average musicians ratings fell within a narrow range of 5.2–6.1, with the exception of AH which was slightly higher at 7.3), so there was insufficient variation between halls for it to be a basis of discriminating between them; whereas, the ‘Reverberance’ was clearly inadequate in some of the regional auditoria on the ACO2 playing tour (the mean ‘Rev’ was as low as 0.8, but ranging to 6.2) and hence had a significant impact on OAI ratings. Similarly, for the ACO Collective tour ‘Reverberance’ showed variability across the different halls (mean ‘Rev’ between 1.5–4.6). Sanders [2003] and Dammerud [2009] also found the importance of reverberance may be disguised when only halls with adequate reverberance are considered.

It should also be noted that the ‘Reverberance’ scale was set up with the optimal rating being 5; a rating of 0 indicated the auditorium was too dry and a rating of 10 indicated the auditorium was overly reverberant. Therefore, a linear relationship between OAI and Reverberance is not necessarily expected. The fact that a linear trend was observed between OAI and Reverberance indicates that many of the auditoria were too dry (particularly on the ACO2/ACO Collective tours) and with increasing Reverberance the OAI ratings increased. Far fewer auditoria were observed to be overly reverberant (and those which were only slightly above the optimum), so a trend of decreasing OAI with increasing 'over reverberant' ratings was not strongly observed.

'Visual Impression' was included on the survey to gauge if this had any impact on the OAI. In all datasets a significant correlation was observed between Visual Impression and OAI (with correlation coefficients of $r = 0.55$, 0.52, and 0.51 for ACO, ACO2 and ACO Collective respectively). This may indicate Visual Impression was subconsciously impacting musicians' ratings of OAI. However, it is difficult to say this conclusively with the data available. Additionally a non-casual relationship between high acoustic ratings and good visual impression could be expected since in purpose-built halls a lot of consideration is given to visual impression and additionally to acoustic design, and like-wise in multi-purpose or regional halls less consideration would be given to visuals and also to acoustics. Therefore an underlying relationship between effort into visual aspects of a concert hall and effort into acoustic design of a concert hall may inherently exist.

Based on ratings of OAI, the most preferred auditorium from the ACO tour was Perth Concert Hall (PH). PH was significantly better than all auditoria except Adelaide Town Hall (AH) and Sydney Recital Hall, Angel Place (AP), at a 1% or 5% level. PH was the highest rated (or equal highest rated) auditorium on OAI for 10 out of the 15 musicians who completed questionnaires. The lowest rating on OAI given for PH was 7.5 (out of 10), indicating it was well liked by every musician surveyed. Based on the orchestra average, the least preferred auditorium was Queensland Performing Arts Centre (QC); however, it was only significantly worse than AH and PH (at a 1% level). It was rated as the worst auditorium (or equal worst) by only 4 out of the 15 musicians surveyed. Wollongong Town Hall (WH) (the second worst auditorium when considering an orchestra average) was actually rated as the worst auditorium (or equal worst) on OAI by 6 of out of the 15 musicians. The best rating of OAI for QC was actually 9 (out of 10); so whereas PH was universally liked, QC was not universally disliked. When examining the median, it becomes clear that for the majority of musicians WH was actually the least preferred auditorium. In fact, in QC it appears the orchestra were not in consensus about the acoustics. QC was polarising, and while the majority of musicians rated it well, a small number gave very low scores on OAI (as low as 1/10).

Notably, all ACO auditoria rated well on average (i.e. 5/10 or greater), which was not the case for the more regional halls in the ACO2 and ACO Collective tours.

Based on ratings of OAI, the most preferred hall from the ACO2 tour was Bellingen Memorial Hall (BEL). BEL was significantly better than all the other halls in the study (at 1% or 5% level), except CLE and MUL. The least preferred hall was NAM, and it was statistically significantly worse than all other halls in the study, except GOL and BUN. Between the best and worst rated halls, some but not all differences were observed as statistically significant based on OAI ratings, see Table 3.8. Compared to the ACO data, the ACO2 results actually showed more variation in subjective characteristics, indicating clear difference between the auditoria on the tour. Interestingly on those scales which were most important to the musicians (most highly correlated with OAI) there is generally significant variation between ratings in different halls, commonly average ratings below 2 and above 7.5 for subjective characteristics. However, for those subjective characteristics found to be less important in this study often there is minimal variation between halls for ACO2; such as, 'hearing self' and 'clarity'. For the case of 'hearing self' it is likely this criteria was simply met in all halls, and no longer impacted musician assessment. This is likely to be because the chamber orchestra in the study involved only strings which means it was unlikely any instruments were overly loud and impacting musicians ability to hear their own sound (whereas loud brass instruments may cause issues with 'hearing self' within a symphony orchestra).

A principal component analysis was also conducted to further examine how the subjective attributes on the questionnaire related to each other. ACO and ACO2 datasets were analysed both separately and pooled together. For ACO all the attributes shown to correlate with OAI also correlated with principal component 1 (PC1). It appears that for ACO most attributes contribute to PC1, and PC1 could possibly be used as an "overall impression" scale. Although, the questionnaire also included 'overall acoustic impression' which asked musicians to indicate their rating between 'very poor' and 'very good'. For ACO, principal component 2 (PC2) was most strongly correlated with 'Warmth' and also correlated 'Timbre' and 'Reverberence'. Lastly, 'Clarity' (and 'Hearing Self') were also reasonably correlated with PC2, with a difference in sign indicating an inverse relationship between Warmth/Timbre/Reverberance and Clarity/Hearing Self. This reinforces the idea that there is an optimum Reverberance that balances the need for sound quality against the ability to hear all parts clearly. For ACO2 again most subjective attributes correlated with PC1, with

'Echoes' being one notable exception. PC2 correlated most strongly with 'Echoes' (as well as 'Clarity' and 'Hearing Self'). PC3 correlated mostly with 'Warmth'. As expected for ACO and ACO2 combined all attributes correlated somewhat with PC1, except 'Warmth' and 'Echoes'.

Overall, it appears for ACO an 'underlying variable' PC1 (which correlates with most of the key subjective attributes) could be used to compare to acoustic measurements. However, since these key subjective attributes also correlate with OAI, acoustic measurements could equally be compared to this scale. PC2, which correlated most strongly with 'Warmth', indicates one factor being assessed differently by musicians. From Figure 3.4, 'Warmth' was rated high in PH and rated low in AP, but there was little variation noted in 'Warmth' in the other six halls, which makes it difficult to use this scale to distinguish between the halls and to use this scale for comparison to acoustic measurements. In Chapter 6 musicians survey results are discussed in comparison to acoustic measurements, and for this purpose OAI is used, since based on the principal component analysis with ACO data PC1 is a combination of most subjective scales and these scales also correlate with OAI.

One general comment from a musician was *"These are complicated questions. I'm always too busy trying to get through the concert and can't concentrate on all this."* This indicates that, as mentioned by others, musicians may actually struggle to assess the conditions of halls on multiple dimensions [Gade, 2010, Chiang et al., 2003]. Another general comment from a musician was *"As I did not read questionnaire til after the concert, I wasn't particularly listening for these things, so I'll be more aware next concert."* These kind of comments highlight some of the difficulties around subjective surveying with musicians. However, sending the questionnaire with the musicians on tour attempted to minimise the issues around acoustical memory, and familiarity with the questionnaire during concert. Additionally, one musician commented *"I have played here for many years so may have a negative bias against the venue"* (in regard to HH). This indicates musicians are aware that they may become biased towards certain auditoria. In his study Dammerud [2009] excluded 'home auditoria' to avoid bias. This is less of an issue in our study, where the ACO performed in a range of different auditoria during a tour. However, musicians will have varying degrees of familiarity with auditoria (depending on personal experience) and obviously this cannot be completely eliminated as a factor.

3.8 Conclusion

In this chapter surveying with three chamber orchestras has been presented. The data presented here will be discussed in depth in comparison to acoustics measurements on stage and in the stalls of auditoria in Chapter 6. In the case of chamber orchestra musicians playing on stage in purpose built auditoria, it appears the key subjective acoustic attributes (which impact overall acoustic impression) are 'Ensemble', 'Support' and 'Timbre'. In the case of chamber orchestra musicians playing on stage in more general purpose halls (where reverberance may be inadequate in some cases) this list must be extended to include 'reverberance'. Therefore, it appears reverberance is a highly important acoustic attribute, which must be met for a good rating on overall acoustic impression, but it is not alone a sufficient requirement for optimal stage acoustics. This supports the work of others such as Sanders [2003] and Dammerud [2009]. Generally good agreement was observed between musicians within playing groups; perhaps an exception to this was QC in the ACO tour, which had the highest standard deviation and appeared to be well-liked by most but strongly disliked by a few. The datasets which are most useful to compare to objective acoustic measurements are the ACO dataset and the ACO2 dataset, where the majority of musicians in the orchestra responded to the questionnaire and frequently significant differences between auditoria assessments of overall acoustic impression were observed (at a 1% or 5% level). The ACO Collective dataset had a lower response rate, and subsequently it was more difficult to distinguish between the auditoria in the study.

Chapter 4

Investigating the effect of a chamber orchestra on direct sound and early reflections on stage using BEM modelling

4.1 Introduction

Acoustic parameters, derived from impulse response measurements on stage, have been used with limited success to characterise the subjective experience of musicians playing on stage. For example, in spite of their general acceptance for stage acoustics characterisation, Dammerud [2009] did not find a correlation between subjective musician ratings and the ST_{early} parameter proposed by Gade [1989c]. One reason for the lack of subjective relevance of such stage acoustic measures may be that they are often derived from measurements undertaken on unoccupied stages, whereas in the real playing experience the on-stage sound field may be impacted by the presence of on-stage objects, including the performers.

To study the acoustics of occupied concert halls and occupied concert hall platforms a common approach is scale modelling [Xiang and Blauert, 1993, Jeon and Barron, 2004, Dammerud and Barron, 2010]. In a limited number of studies full scale measurements have been conducted [Skålevik, 2007, Wenmaekers et al., 2016]. However, most often measurements on stage without stage objects present, or with only chairs and music stands, are used because of the practical difficulties and lack of repeatability associated with doing acoustic measurements with an orchestra present.

Acoustic parameters defined with 'early' time intervals are commonly used to assess ensemble playing conditions. The time period used to define 'early' varies: Gade [1992] has defined 20–100 ms as 'early' for the stage support parameter ST_{early}, Dammerud [2009] has defined early as 0–80 ms for G_{e} (early sound strength) and also examined G_{7-50} with a time interval of 7–50 ms. Others have also investigated very early time intervals, such as LQ_{7-40} defined with a time interval of 7–40 ms [van Den Braak and van Luxemburg, 2008]. The support measures have also been adapted to allow for across-stage measurements with source-receiver distance greater than 1 m by Wenmaekers et al. [2012], denoted as $ST_{\mathrm{early,d}}$, with the early time interval defined as '10–*delay*' ms, where *delay* is the source-receiver distance divided by speed of sound.

In this chapter, a boundary element method (BEM) model of a chamber orchestra has been developed to investigate the on-stage acoustic conditions for a chamber orchestra. This model has been validated against measurements in a hemi-anechoic chamber and the details of the validation are provided in Appendix D. To further validate the BEM model for this investigation, full scale measurements with a real chamber orchestra were also conducted in an auditorium, as are discussed in Section 4.3 (see also Appendix E for a discussion of the truncation times selected to isolate first-order reflections). The full scale measurements showed that the BEM produces realistic results, and the BEM model was then used to investigate two different stage enclosure sizes.

Traditionally, stage parameters have been omnidirectional, however previous studies have considered whether the directionality of on-stage sound fields is subjectively important to musicians [Meyer and Biassoni de Serra, 1980, Meyer, 1986, Dammerud et al., 2011, Guthrie, 2014]. This study focuses on the effect of the orchestra on direct sound and also first-order enclosure reflections, and each first-order reflection is investigated individually to demonstrate the effect of the orchestra depending on the arrival direction. This is of particular interest in this dissertation as the directionality of on-stage sound fields in real auditoria is also considered via stage measurements with a spherical microphone array (Chapter 5).

4.1.1 Effect of orchestra on on-stage sound fields for seated orchestras

In this chapter the effect of a standing chamber orchestra (but seated cello players) on on-stage sound fields is discussed. The orchestra investigated in this work is representative of the configuration used by the chamber orchestras surveyed during concert tours (Chapter 3). As outlined in Section 2.1 (Chapter 2), much of the work in the literature focuses on seated musicians. Earlier work by the candidate also explored on-stage sound fields for seated chamber orchestras.

Dammerud and Barron [2010] studied on-stage attenuation of direct sound (and floor reflection) using a scale model (1:25) of a symphony orchestra, and found that for the 500 Hz octave and above there was significant deviation from the empty stage result. Skålevik [2007] conducted full scale measurements and found the effect of a symphony orchestra on on-stage sound fields was significant for the 500 Hz octave band and above for a single path through a full symphony orchestra (path length 11.7 m). Other work by Dammerud [2009] has used ray-tracing to model a symphony orchestra on stage, using the scale model results (including a scale model stage enclosure) for validation. However, the agreement between the ray-tracing model and scale model was poor for source-receiver distances between 5 and 9 m. Ray-tracing does not fully account for wave interference effects, diffraction and specific characteristics of scattering and subsequently appears to be an inadequate model to investigate within-orchestra attenuation for shorter source-receiver paths, particularly those between 5 and 9 m [Dammerud, 2009]. Wenmaekers et al. [2016] examined the effect of a symphony orchestra on stage with a dummy orchestra consisting of mannequins (the sound absorption properties of these mannequins validated with measurements in a reverberation chamber). The dummy orchestra was used on fives stages, and attenuation of direct sound was examined to compare to results from Dammerud and Barron [2010]. Attenuation by the dummy orchestra was 3–6 dB greater than by Dammerud and Barron's scale model orchestra for the same source-receiver distances through the orchestra (distances between 3–16 m). Wenmaekers et al. [2016] also considered the effect of the orchestra on early sound parameters (namely ST_{early} and $ST_{\text{early,d}}$); the difference between occupied and empty condition was 2 dB for ST_{early} (slightly less for $ST_{\text{early,d}}$ for a 1 m source-receiver distance).

Initial work by the candidate used BEM to model seated chamber orchestras and is presented in Panton and Holloway [2014] and Panton and Holloway [2015] (see Appendix A). Panton and Holloway [2014] validated the seated chamber orchestra against full-scale measurements by Krokstad et al. [1980] and then examined sound propagating through a seated chamber orchestra with the use of contours plots. The contour plots demonstrate visually how a seated chamber orchestra is virtually 'invisible' to sound waves at low frequency (i.e. 125 Hz octave and below), but show increasing effect on on-stage sound field with higher frequency. Panton and Holloway [2015] used the same validated seated chamber orchestra model and explored different paths through the chamber orchestra, finding for a given source-receiver distance that octave band average attenuation was relatively constant regardless of the specific path through the orchestra. This work also explored random perturbations to the orchestra configuration and found minimal impact when 0.5 m distance was cleared around the source and receiver location.

4.1.2 Use of BEM modelling: advantages and disadvantages

In this chapter boundary element method (BEM) is used to model a chamber orchestra, and explore the effect of the orchestra on on-stage sound fields. This has several inherent advantages. A detailed and systematic study can be conducted considering paths within the orchestra individually and first-order enclosure reflections individually. There is flexibility in what can be studied, for example in this chapter a case study looks at tilting side wall to reduce attenuation of lateral reflections. Also BEM is an accurate method which fully accounts for diffraction and scattering effects and is particularly useful when investigating low frequency and short source-receiver distances. This is in contrast to energy or ray-tracing methods, which can only treat wave effects empirically. Such effects are most prominent at wavelengths comparable in scale to the principal geometric features of the scattering bodies, that is from low frequencies up to roughly the upper end of the 1 kHz octave band ($\lambda = 240$ mm). The BEM models this range of frequencies particularly well. However every doubling of frequency requires four times as many elements to maintain the wavelength to element size ratio, requiring around 16 times more memory and comparable increases in computational time. Thus it is not yet practical to model an orchestra at high frequencies using BEM. Similarly very large orchestras, full complex stage enclosures or multiple symmetry planes are beyond the practical limits of BEM with current every-day computing resources. In this work the highest octave band explored was 1 kHz, whereas commonly used stage parameters (such as ST parameters) are averaged over 250–2000 Hz octaves.

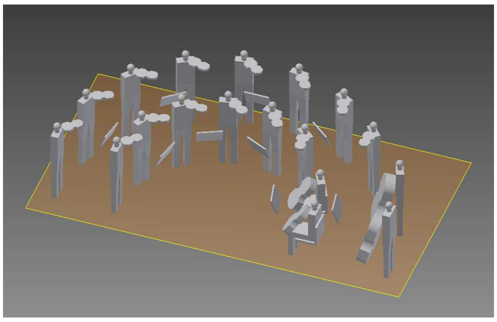


Figure 4.1: Final chamber orchestra model as modelled in Autodesk Inventor.

4.2 BEM model of a chamber orchestra

4.2.1 Introduction

The chamber orchestra model with instrument geometries included is shown in Figure 4.1. The musician geometry and the complex impedance values applied to musician geometry were chosen based on a validation process which is outlined in Appendix D. The inner-most circle of musicians has a radius of 2 m and the outer circle of musicians has a radius of 3.2 m. Music stands are located 0.8 m forward of musicians' heads at a height of approximately 1.2 m (to the base of the stand) for standing musicians and approximately 0.75 m (to the base of the stand) for seated musicians, with each stand shared between two players in accordance with usual practice. In the BEM model omnidirectional source and omnidirectional receivers were simulated. Additionally, a perfectly reflective stage floor was represented with a symmetry plane.

For on-stage measurements, Gade [1992] has suggested removing all stage furniture within a 2 m radius of the source and receiver to avoid significant influence from the nearby objects on direct sound estimation. For a chamber orchestra on stage a 2 m radius around both the source and receiver would equate to removing almost all the on-stage objects. For smaller stages (such as those which may be unsuitable for a symphony orchestra but used by a chamber orchestra), Gade suggests empty stage measurements.

The aim of this study is to consider how representative unoccupied stage measurements are for a chamber sized orchestra. The approach in this study was therefore to clear any objects that have any part within a radius of 0.5 m so that most of the orchestra would remain. The cleared radius of 0.5 m generally equated to the musician at the source or receiver location and in some cases the nearest music stand. This left a reasonably realistic on-stage setup, and this is in line with the method used by others when investigating the impact of an orchestra on on-stage sound fields [Dammerud and Barron, 2010, Wenmaekers et al., 2016].

4.2.2 Effect of stage objects on direct sound and floor reflection

In this section the attenuation of the direct sound and floor reflection and the contribution of early reflections from nearby stage objects are investigated using the validated BEM model. Several cases are presented with various source and receiver locations within the chamber orchestra. The source and receiver locations have been selected as player locations with both 1.5 m above the stage floor. For this analysis a quantity ΔL is defined as the SPL at the receiver relative to the SPL of the direct sound only (in the absence of any orchestra or floor) at the same receiver location. As such,

$$\Delta L = \mathrm{SPL}_{\mathrm{receiver}} - \mathrm{SPL}_{\mathrm{direct}} \tag{4.1}$$

where $\mathrm{SPL}_{\mathrm{receiver}}$ is the SPL at a receiver on stage and $\mathrm{SPL}_{\mathrm{direct}}$ is the 'free field' direct SPL at the same receiver location (as used by Dammerud and Barron [2010] to investigate on-stage sound fields for symphony orchestras).

The results denoted as 'Analytic' in the following sections have been computed from direct sound and floor reflection (i.e. the empty stage solution), which will have a limiting value of +6 dB when these two are in phase and of equal amplitude.

Three different source-receiver cases have been considered, as shown in Figure 4.2. For Case 1 the attenuation between two players across roughly the geometric center of the orchestra is investigated, for Case 2 the attenuation between the left-most player in the orchestra and the right-most player in the orchestra is investigated and for Case 3 the attenuation between the concertmaster (i.e. principal first violin) and a back row player in the orchestra is investigated. The empty stage (Analytic) and occupied stage (BEM) solutions are shown for Case 2 in Figure 4.3 over the full frequency range; the same results are not presented for Cases 1 and 3 but were similar, although Case 3 generally showed less attenuation across the full frequency range than the other two cases.

From the un-averaged curve of ΔL versus frequency (Figure 4.3) it is evident that there is

Table 4.1: Difference between octave band average values of BEM ΔL and Analytic ΔL (dB) for direct sound and floor reflection only for the three orchestra configurations investigated (Cases 1, 2 and 3).

Octave (Hz)	Case 1	Case 2	Case 3
125	0.1	0.5	−0.1
250	−0.8	3.9	−2.8
500	−6.0	−2.6	−1.8
1000	−6.0	−4.0	−0.5

general agreement between the empty stage (Analytic) and BEM solution in terms of gross features. However, dips due to destructive interference may be frequency shifted and have different magnitudes — this is due to the modified path lengths because of the presence of the chamber orchestra and to a small extent the surface absorption of the musicians. Additional dips and peaks also arise from a proliferation of multiple sound paths.

The differences after octave band averaging between the Analytic case (empty stage) and the BEM case (occupied stage) are presented in Table 4.1. Case 1 shows low attenuation at the 125 Hz and 250 Hz octave bands, but significant attenuation of the direct sound and floor reflection for 500 Hz and 1000 Hz octave bands. Case 2 shows significant effect of stage objects at all frequencies above the 125 Hz octave band. Notably the value of ΔL is positive at 250 Hz indicating that the SPL on the empty stage at the receiver location is actually lower than on the occupied stage. From Figure 4.3 we can see that this is because for the occupied stage solution the destructive interference between the direct sound and floor reflection is significantly reduced and the constructive interference at higher frequencies is shifted into the 250 Hz octave band. Case 3 shows minimal effect from stage objects across the whole frequency range of interest, with the exception of the 250 Hz octave band.

4.2.3 Effect of stage objects on first-order reflections

In this section the effect of the chamber orchestra on first-order reflections from the stage enclosure is investigated. The mesh required to implement a stage enclosure in the BEM model would be too large for the model to be feasible to solve. Instead walls and ceiling have been modelled one at a time using symmetry, by creating an image of the orchestra and adjusting the omnidirectional source location in the BEM model appropriately. An example of the setup for investigating the left stage wall first-order reflection for the typical enclosure

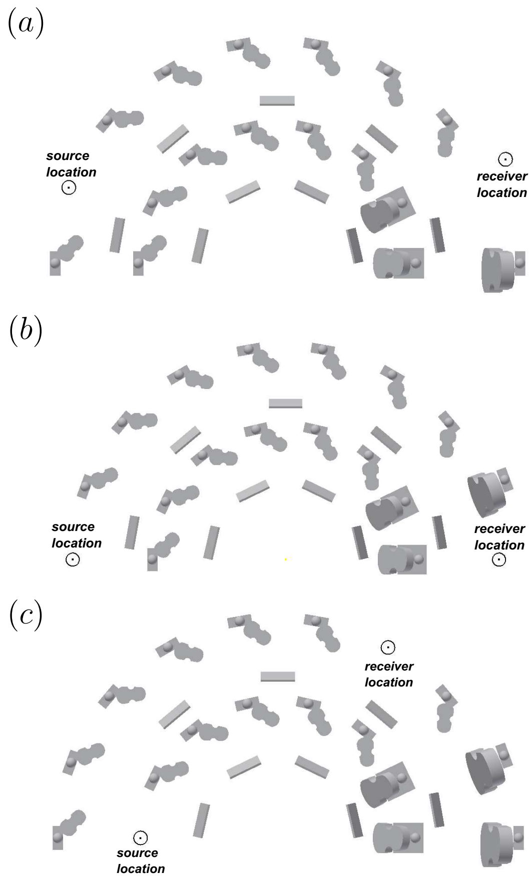


Figure 4.2: The source-receiver locations for the three cases investigated, (a) Case 1 with source-receiver distance of 6.3 m, (b) Case 2 with source-receiver distance of 6.4 m and (c) Case 3 with source-receiver distance of 4.5 m.

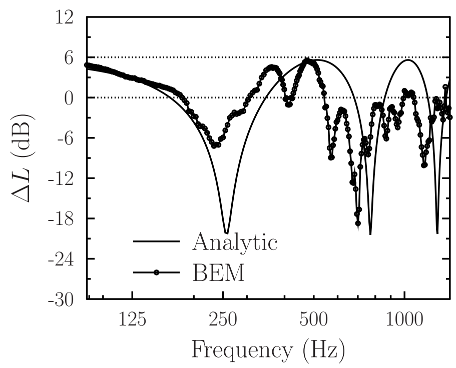


Figure 4.3: Case 2 orchestra configuration and sound field results for direct sound and floor reflection only. ΔL versus frequency (direct sound and floor reflection only) (Analytic = empty stage, BEM = occupied stage)

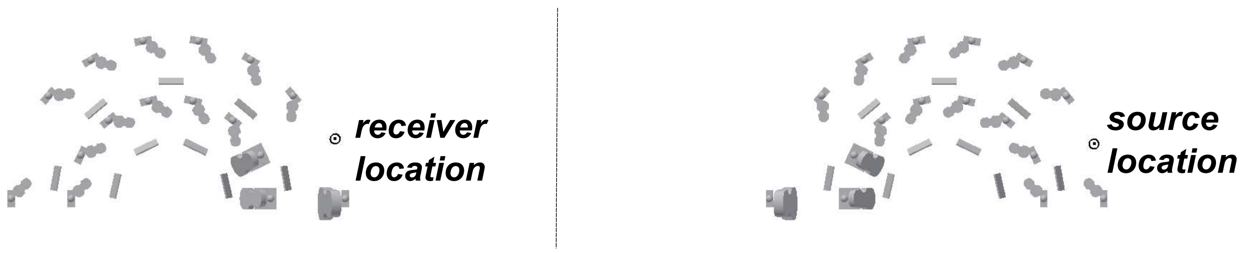


Figure 4.4: The setup used to investigate the left wall reflection for Case 1. The left wall reflection has been investigated by creating a mirror image of the orchestra, and the source has been moved as shown (receiver location is unchanged from direct sound investigation). The dashed line is the left wall.

is shown in Figure 4.4 in which the orchestra is mirrored about the left enclosure wall. The receiver location remains unchanged from that used in the investigation of the direct sound, but the source is moved to the image to give the correct source-receiver geometry for the left wall first-order stage reflection. The source used to investigate the direct sound is removed in this analysis, so the stage enclosure reflection attenuation can be considered separately. 'Left', 'right' and 'back' in this study are defined from the perspective of a musician on stage facing the audience. This method has the advantage of allowing the first-order stage enclosure reflections to be studied individually, which is of interest because physical measurements are generally studied as impulse responses, and further because the complementary work involving stage measurements in auditoria assessed by chamber orchestras has included analysis of both the spatial and temporal response (see Chapter 5).

The specific effect of stage objects on first order reflections (and subsequently on-stage acoustic measures) will depend on the stage enclosure size and shape. Two stage enclosures sizes have been investigated. The dimensions of the first stage enclosure are 15.5 m wide and 8 m deep and 12 m high (height of ceiling above stage), which are typical of purpose-built concert hall stages that are included in the subjective and objective survey of stage acoustics for chamber orchestras, and this stage enclosure will be referred to as the 'typical' enclosure size. Also, a 'small' stage enclosure has been investigated, the dimensions of which are 11.4 m wide, 6 m deep and 9 m high. The dimensions of the 'small' enclosure were chosen to agree with the stage enclosure size used in the full scale measurements with a chamber orchestra in an auditorium presented in Section 4.3.

In this section the attenuation of first-order reflections for the typical and small enclosures is investigated. The arrival times for first-order reflections (relative to the direct sound) for source-receiver locations in Cases 1, 2 and 3 are shown in Figure 4.5 for the typical and small enclosures. First-order reflections, and the corresponding floor reflection, are included in the BEM analysis, but no other second order reflections are considered.

The results for difference between BEM and Analytic for the first-order reflections for Cases 1, 2 and 3 are summarised in Table 4.2 for the typical and small enclosures. To illustrate typical detail ΔL is plotted against frequency for each first-order reflection for Case 1 with the typical enclosure in Figure 4.6. ΔL is defined in the same manner as in Section 4.2.2 as the difference between the SPL at the receiver and the SPL at the same source-receiver distance in a free field.

In all cases the ceiling reflection is not significantly affected by the presence of the orchestra at any frequency. This result is expected because the ceiling reflection path does not pass through the orchestra when traveling from source to receiver, and thus would only be minimally impacted by some reflections from nearby stage objects.

For Case 1 typical enclosure, there is minimal difference in first-order reflection with and without the orchestra in the 125 Hz octave. However, there is notable attenuation for the 1000 Hz octave band for all the first-order reflections (as high as 6 dB), with the exception of the ceiling reflection. For the intermediate octave bands (250 Hz and 500 Hz) the effect is varied. The similarity for 250 Hz and 500 Hz between the empty and occupied stage solutions is dependent on how the destructive interference between the direct sound and floor reflection is altered by the presence of the stage objects. For Cases 2 and 3, the findings are very similar to Case 1, with high attenuation at the 1000 Hz octave band, varied levels of attenuation at 250 Hz and 500 Hz, and minimal attenuation for the 125 Hz octave.

Regarding the small enclosure size, again none of the first-order reflections are attenuated by more than 1 dB at the 125 Hz octave band, and there is minimal difference in occupied and empty stage solutions for the unobstructed ceiling reflection. Again for this enclosure size there is generally high attenuation in the 1000 Hz octave band and varied levels of attenuation at 250 Hz and 500 Hz.

The first-order reflections are combined to give a 'Stage Walls Combined' (SWC) quantity. In Table 4.2 the difference between occupied and empty SWC is given and this quantity is labelled $\mathrm{SWC}_{\text{occ. - empty}}$ (where occ. stands for occupied). The definition of this quantity is

$$\mathrm{SWC}_{\text{occ. - empty}} = 10\log_{10}\left(\frac{(\sum p_i^2)_{\mathrm{BEM}}}{(\sum p_i^2)_{\mathrm{Analytic}}}\right) \tag{4.2}$$

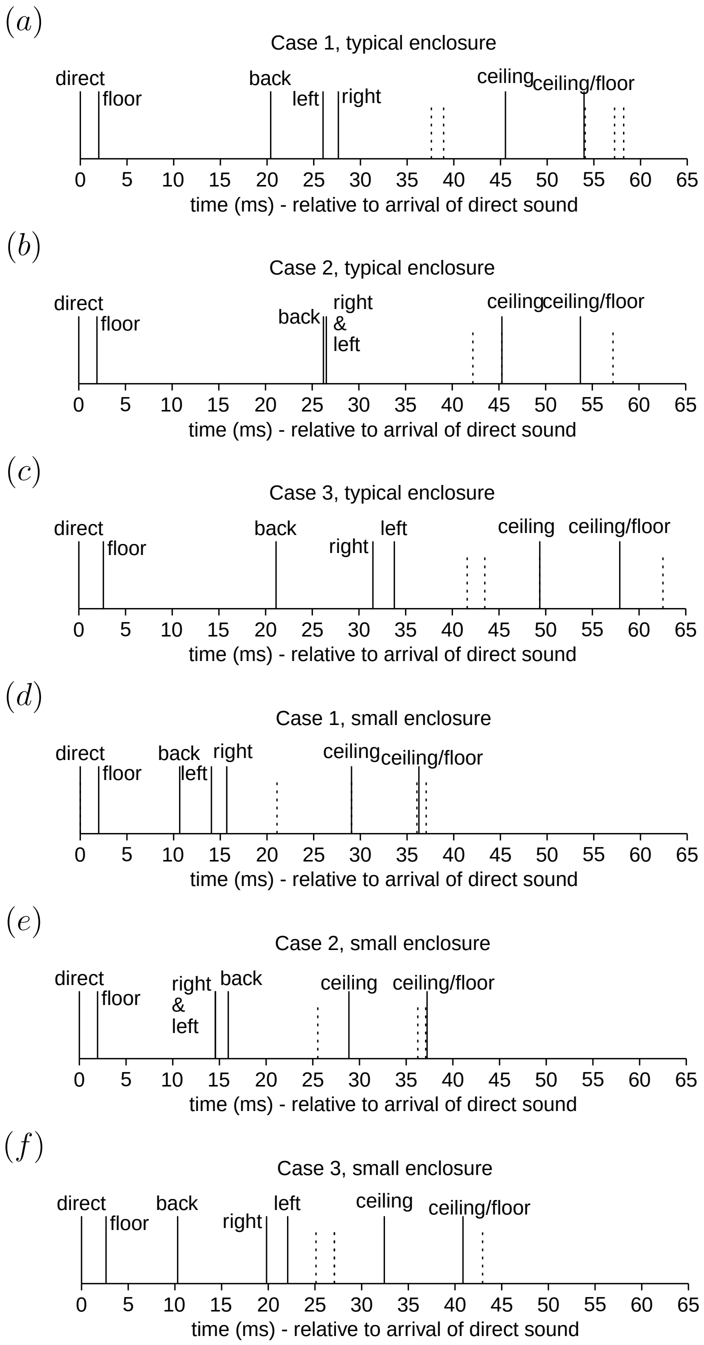


Figure 4.5: Arrival of first-order reflections (relative to arrival of direct sound) for typical and small stage enclosure, with source and receiver locations as used in Cases 1, 2 and 3. The first-order reflections are shown with a solid line, and initial second-order reflections (not accounted for in BEM model) are shown with a dashed line. Each first-order reflection is also closely followed by a floor reflection (not shown), with the exception of reflection via ceiling and floor which is shown as this is more widely spaced and is the final reflection accounted for in the BEM model. Each figure is labelled with the enclosure size and case number.

where $p_i = p_{\text{direct}}$, p_{back}, p_{left}, p_{right} and p_{ceiling} and are the pressures from direct sound, back wall, left wall, right wall and the ceiling respectively. Note, the direct sound and each first-order reflection includes the corresponding floor reflection, since a symmetry plane was in place to represent the floor. It should also be noted that the square of the pressure magnitude was summed (rather than complex pressures being added before squaring their resultant magnitude) because in the auditorium used for validation (see Section 4.3) the ornate surfaces would produce some spatial and temporal diffusion, thus the reflections would behave as incoherent sources, not perfectly coherent sources. However, the floor reflection will be coherent since the floor is perfectly flat and rigid, and this is accounted for by including the floor reflection in the BEM model (with use of a symmetry plane). This method gives good agreement with the auditorium measurements presented in Section 4.3. The pressure squared sum method is therefore also used for the 'typical' enclosure BEM results since most auditoria would have similarly diffusing walls and a flat floor. Also included in Table 4.2 is $\text{SWC}_{\text{occ. - empty}}$ with the direct sound excluded. Direct sound is excluded in some common stage parameters, such as ST_{early} where the early is defined as 20–100 ms [Gade, 1992], LQ_{7-40} where early is defined as 7–40 ms [van Den Braak and van Luxemburg, 2008] and a variation on early support $ST_{\text{early,d}}$ where 10 ms is used instead of 20 ms to start the early time interval [Wenmaekers et al., 2012]. Direct sound is also included in some stage parameters, such as G_{0-80} where early is defined as 0–80 ms [Dammerud, 2009].

Figure 4.5 suggests that for the typical stage enclosure, $\text{SWC}_{\text{occ. - empty, excl. ceiling}}$ is equivalent to truncating the signal at around 40 ms, while $\text{SWC}_{\text{occ. - empty, incl. ceiling}}$ is equivalent to truncating the signal at around 60 ms; however, it should be noted there would generally be second order stage enclosure reflections occurring before the ceiling, which were not considered in the BEM model.

4.2.4 Effect of stage objects for varying reflection arrival elevation angle

This section considers the effect of the chamber orchestra on lateral reflections arriving at angles between the horizontal and vertical plane, such as those caused by an angled reflector or angled side wall. The source and receiver locations were those of Case 1, and angled left wall reflections were considered (where θ is the angle the left side wall is tilted from vertical), as shown in Figure 4.7. The angle θ was varied from 0° (left wall reflection case

Table 4.2: Difference between octave band average values of BEM ΔL(dB) and Analytic ΔL(dB) for Cases 1, 2 and 3, for the typical stage enclosure and the small stage enclosure, for first-order reflections. $\mathrm{SWC}_{\mathrm{occ.\ -\ empty}}$ is discussed in Section 4.2.3 and is defined in Eq. 4.2.

Case		Typical				Small			
	Octave (Hz)	125	250	500	1000	125	250	500	1000
1	Direct (and floor)	0.2	−0.8	−6.0	−6.0	0.2	−0.8	−6.0	−6.0
	Back Wall	−0.4	0.4	−1.2	−1.9	−0.8	0.5	−0.2	−4.7
	Right Wall	0.1	−1.3	−2.5	−5.2	−0.1	−2.2	−2.3	−5.2
	Left Wall	0.4	−2.2	−5.2	−6.2	0.1	−2.7	−4.8	−5.9
	Ceiling	0.1	−0.8	0.3	−0.2	0.1	−0.8	−0.2	−0.2
	$\mathrm{SWC}_{\mathrm{occ.\ -\ empty,\ excl.\ ceiling}}$	0.0	−0.9	−4.7	−4.6	−0.1	−1.2	−4.1	−5.5
	(exclude direct)	(−0.1)	(−0.9)	(−1.6)	(−3.6)	(−0.3)	(−1.3)	(−1.4)	(−5.2)
	$\mathrm{SWC}_{\mathrm{occ.\ -\ empty,\ incl.\ ceiling}}$	0.0	−0.9	−4.3	−4.3	−0.1	−1.1	−3.7	−4.8
	(exclude direct)	(0.0)	(−0.9)	(−1.2)	(−3.2)	(−0.2)	(−1.2)	(−1.1)	(4.2)
2	Direct (and floor)	0.5	3.9	−2.6	−4.0	0.5	3.9	−2.6	−4.0
	Back Wall	−0.5	−1.5	−3.3	−3.8	−0.8	−3.8	−2.0	−3.7
	Right Wall	0.2	−2.3	0.3	−3.3	0.1	−1.6	−0.7	−2.3
	Left Wall	0.5	−1.2	−1.9	−4.6	0.3	−1.4	−2.8	−5.3
	Ceiling	0.1	−0.7	−0.5	−0.1	0.1	−0.3	−0.4	−0.2
	$\mathrm{SWC}_{\mathrm{occ.\ -\ empty,\ excl.\ ceiling}}$	0.3	0.4	−2.5	−3.9	0.1	0.0	−2.4	−3.8
	(exclude direct)	(0.1)	(−1.7)	(−1.4)	(−3.9)	(−0.1)	(−2.1)	(−1.7)	(−3.6)
	$\mathrm{SWC}_{\mathrm{occ.\ -\ empty,\ incl.\ ceiling}}$	0.3	0.3	−2.3	−3.6	0.1	0.0	−2.2	−3.4
	(exclude direct)	(0.1)	(−1.5)	(−1.0)	(−3.3)	(−0.1)	(−1.8)	(−1.3)	(−3.0)
3	Direct (and floor)	−0.1	−2.8	−1.8	−0.5	−0.1	−2.8	−1.8	−0.5
	Back Wall	−0.6	−0.3	1.0	−3.7	−0.9	−0.6	−2.2	−2.0
	Right Wall	−0.6	−0.2	−3.5	−3.8	0.0	−1.0	−3.6	−1.5
	Left Wall	0.00	−1.4	−3.6	−3.9	−0.9	−0.8	−2.5	−3.2
	Ceiling	−0.4	0.1	0.0	−0.4	−0.6	0.00	−0.9	−0.1
	$\mathrm{SWC}_{\mathrm{occ.\ -\ empty,\ excl.\ ceiling}}$	−0.3	−2.0	−1.6	−1.3	−0.4	−2.1	−2.4	−1.2
	(exclude direct)	(−0.5)	(−0.7)	(−0.2)	(−3.8)	(−0.5)	(−0.8)	(−3.0)	(−2.0)
	$\mathrm{SWC}_{\mathrm{occ.\ -\ empty,\ incl.\ ceiling}}$	−0.3	−1.9	−1.6	−1.2	−0.4	−1.9	−2.4	−1.1
	(exclude direct)	(−0.4)	(−0.5)	(−0.2)	(−3.3)	(−0.5)	(−0.6)	(−2.8)	(−1.8)

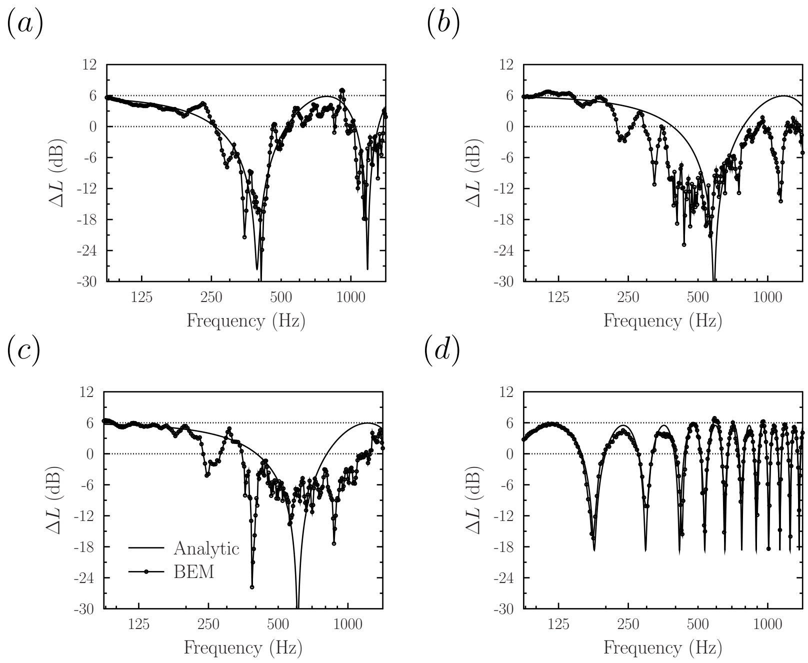


Figure 4.6: ΔL versus frequency for Analytic and BEM solution for Case 1 first-order reflections for the typical stage enclosure (Analytic = empty stage, BEM = occupied stage); (a) back wall reflection, (b) left wall reflection, (c) right wall reflection and (d) ceiling reflection.

for standard enclosure size as presented in Section 4.2.3) to 40 °, and the equivalent source-receiver distance was kept constant (at 15.2 m), thus reflection surfaces were tangent to a common ellipse. The results are graphed in Figure 4.8, where difference between BEM and Analytic (i.e. occupied and empty) is plotted against θ.

The effect of the orchestra reduces rapidly with increasing angle θ for 500 and 1000 Hz octave bands, as the primary source-receiver path progressively clears the orchestra. ΔL approaches 0 dB, which is not surprising as this is the result for the ceiling reflection (effectively θ =90°, albeit with a different source-receiver distance).

The effect on the other hand is relatively independent of angle for 125 and 250 Hz bands. These frequencies have already been shown to be relatively unaffected by the orchestra. Interestingly the 250 Hz octave is consistently lower than the 125 Hz octave, a result also seen in Table 4.2. This may be due to additional interference from the proliferation of paths in the vicinity of the first destructive interference.

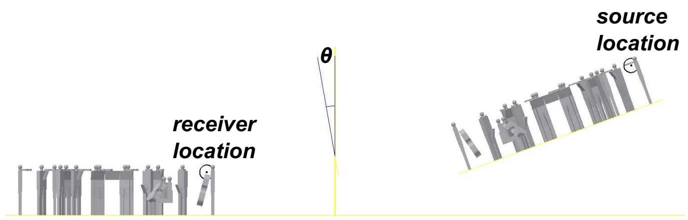


Figure 4.7: Angled chamber orchestra model as modelled in Autodesk Inventor, for angle θ =10°.

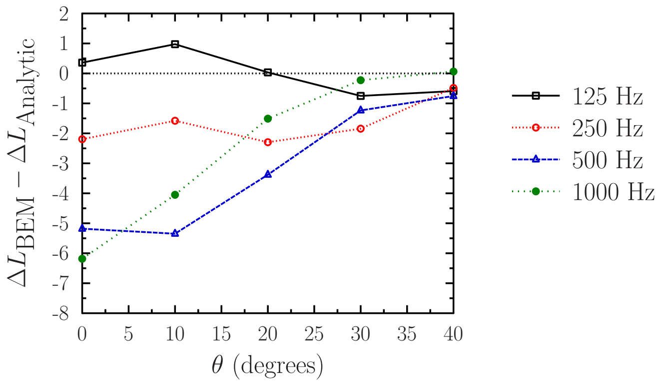


Figure 4.8: ΔL_{BEM}-$\Delta L_{\mathrm{Analytic}}$ as a function of angle θ (as defined in Figure 4.7) for 125–1000 Hz octave bands.

4.3 Full scale measurements in an auditorium with a chamber orchestra

To further validate the use of BEM to model a chamber orchestra, and the use of symmetry in the BEM model to replicate first-order stage enclosure reflections, full scale measurements were undertaken in an auditorium with a chamber orchestra (including music stands, seats, instruments and the musicians themselves). For the auditorium measurements a Brüel&Kjær omnidirectional loudspeaker type 4295 was used, along with an amplifier (Brüel&Kjær power amplifier type 2734) and computer software with an audio interface (AARAE release 7 with Fireface UCX interface). An exponential sweep with duration 30 s, start frequency 50 Hz and end frequency 20 kHz was used in impulse response measurements, and the receiver used was a Brüel&Kjær omnidirectional microphone type 4910.

The auditorium used for these measurements was the Hobart Town Hall (Tasmania, Australia). Due to the small stage size, the orchestra was set up at the back of the auditorium, which provided an approximate 'shoe-box' stage enclosure with ceiling height of 9.0 m, stage

Figure 4.9: The chamber orchestra setup in the auditorium.

width of 11.4 m, stage depth of 6.0 m (from the front of the ensemble). The source and receiver were both at a height of 1.5 m. Figure 4.9 shows the chamber orchestra in situ in the auditorium. It should be noted that the interior plaster surfaces of the auditorium were quite ornate, and included various sized and shaped alcoves, and these details were not included in the BEM model, and would result in significantly more scattering, rather than discrete reflections.

The same source-receiver configurations used in the BEM model (Cases 1, 2 and 3) were also investigated in the auditorium measurements. Three identical measurements were conducted for each case, between which the orchestra was asked to relax and move around to deliberately introduce small random perturbations to the orchestra configuration. Measurements were also taken on stage with no orchestra present (empty stage), for Cases 1, 2 and 3, for comparison to the occupied stage measurements.

These full scale measurements also had several advantages over the BEM model: higher frequencies could be investigated which are not possible with the BEM model, and higher order reflections could also be considered, where the BEM model investigation was limited to only the first-order stage enclosure reflections.

To investigate the equivalent quantity considered with the BEM model (Eq. 4.2), the occupied and empty stage measurements were compared using $\mathrm{SWC}_{\text{occ. - empty}}$ defined as

$$\mathrm{SWC}_{\text{occ. - empty}} = 10\log_{10}(p_{\text{occupied}})^2 - 10\log_{10}(p_{\text{empty}})^2, \qquad (4.3)$$

where p_{occupied} is the pressure at the receiver with the chamber orchestra present on stage and p_{empty} is the pressure at the receiver with no orchestra present (empty stage), both integrated over suitable time windows to isolate the desired reflections. The quantity $\mathrm{SWC}_{\text{occ. - empty}}$ is plotted as a function of cutoff time for each case in Figure 4.10. Figure 4.10 shows that the difference between 'occupied' and 'empty' is greatest when the signal is truncated to include only the direct sound and floor reflection. When the signal is truncated later to include the early reflections, and in particular when it is truncated to include the unobstructed ceiling reflection (after around 30 ms), the difference between 'occupied' and 'empty' becomes progressively less. However, these results show that over the first 50 ms of the impulse response there are quite significant differences between 'occupied' and 'empty', even when the unobstructed ceiling reflection is included. Between 50–100 ms $\mathrm{SWC}_{\mathrm{occ.\ -\ empty}}$ remains nearly constant, indicating the main differences between 'occupied' and 'empty' on stage are occurring in the 0–50 ms time interval.

Before investigating $\mathrm{SWC}_{\mathrm{occ.\ -\ empty}}$ (Equation 4.3) the impulse responses were truncated. Due to limitations in signal processing, it is impossible to isolate individual reflections without smearing from adjacent reflections, unless there is an appropriate gap where no sound energy in theory arrives, as discussed by Wenmaekers et al. [2012]. The truncated times selected were investigated and this is discussed in detail in Appendix E. In summary, for comparison to the quantity $\mathrm{SWC}_{\mathrm{occ.\ -\ empty,\ excl.\ ceiling}}$ from the BEM model, a cutoff time of 23 ms was selected to isolate reasonably well the direct sound, the back wall, left wall and right wall reflections (prior to the occurrence of the ceiling reflection). Additionally, to compare to the quantity $\mathrm{SWC}_{\mathrm{occ.\ -\ empty,\ incl.\ ceiling}}$, the signal was truncated at 40 ms for Cases 1 and 2, and at 43 ms for Case 3.

The results for measurements compared to BEM are presented in Table 4.3 and for the 23 ms truncation the agreement is generally within 1 dB. The worst result is for Case 1, 1000 Hz and may be explained by the second-order reflections arriving close to 23 ms (see Figure 4.5d).

For the auditorium measurements three trials were conducted and the musicians were asked to relax and move in between trials (to represent some random perturbations in orchestra configuration). The results presented in Table 4.3 are an average of the three trials, however, the random perturbations introduced minimal change to results, with the largest change in $\mathrm{SWC}_{\mathrm{occ.\ -\ empty}}$ (0–23 or 0–40/43 ms truncation) between trials being 0.5 dB (across 125–1000 Hz bands and Cases 1–3).

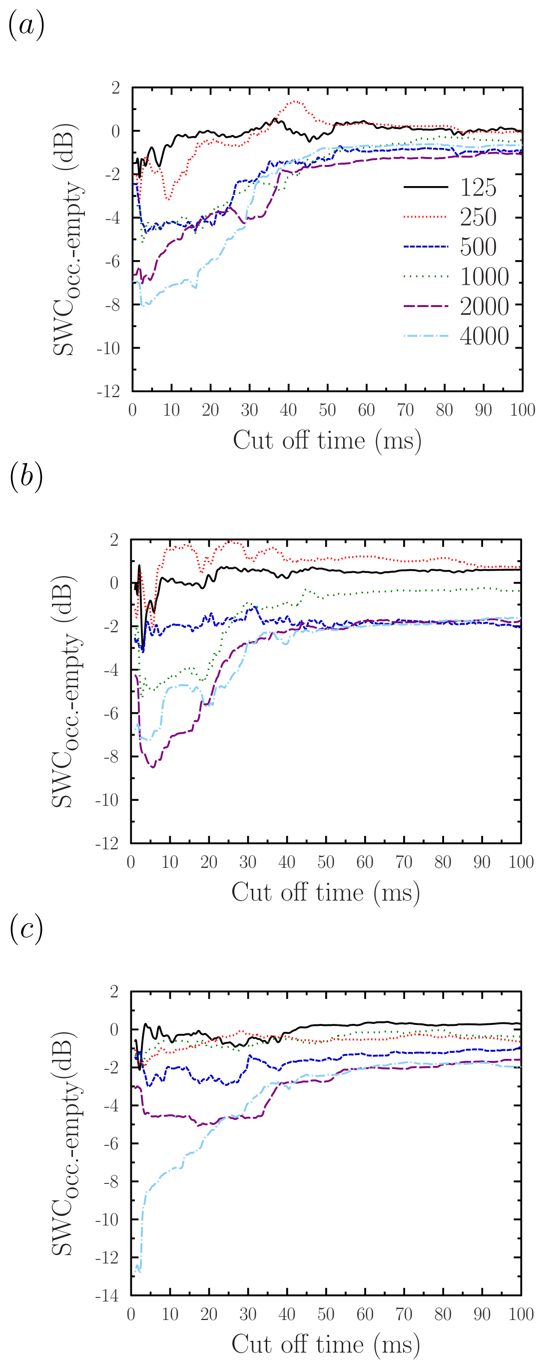


Figure 4.10: $\mathrm{SWC}_{\mathrm{occ.\ -\ empty}}$ (dB), as defined in Eq. 4.3, changing with cutoff time (s) for each case for measurements in the Hobart Town Hall with full scale chamber orchestra; (a) Case 1, (b) Case 2 and (c) Case 3.

Table 4.3: Comparison of $SWC_{occ.\text{ - }empty}$ for measurements truncated with different time intervals and for the equivalent BEM $SWC_{occ.\text{ - }empty}$ quantity for Cases 1, 2 and 3. Note, BEM equivalent values are as listed in Table 4.2. For 2000 Hz octave measurements results only are given.

		0–23 ms			0–40/43 ms		
Case	Octave (Hz)	Measurement	BEM equivalent	Difference	Measurement	BEM equivalent	Difference
1	125	0.0	−0.1	0.2	0.2	−0.1	0.3
	250	−0.3	−1.1	0.9	1.2	−1.1	2.4
	500	−3.8	−4.1	0.3	−1.6	−3.7	2.1
	1000	−3.4	−5.5	2.1	−2.0	−4.8	2.9
	2000	−3.8	-	-	−2.0	-	-
2	125	0.8	0.1	0.7	0.3	0.1	0.2
	250	1.6	0.0	1.6	1.1	0.0	1.1
	500	−1.9	−2.4	0.5	−1.7	−2.2	0.5
	1000	−3.0	−3.8	0.8	−1.0	−3.4	2.4
	2000	−3.8	-	-	−2.0	-	-
3	125	−0.4	−0.4	0.0	0.1	−0.4	0.5
	250	−0.4	−2.1	1.7	−0.5	−1.9	1.4
	500	−2.9	−2.4	−0.5	−1.9	−2.4	0.5
	1000	−0.8	−1.2	0.3	−0.6	−1.1	0.5
	2000	−5.1	-	-	−3.2	-	-

4.4 Discussion

In Sections 4.2.2, 4.2.3 and 4.3 results have been presented showing how a chamber orchestra on stage attenuates, or modifies via scattering, the direct sound and first-order stage enclosure reflections. These findings have implications for the relevance of common on-stage acoustic parameters measured on an occupied, versus an unoccupied stage. This work demonstrates the effect that a chamber orchestra on stage would have on a parameter defined with an early time interval (0–50 ms); generally a 2–5 dB difference was found at 1 kHz without the unobstructed ceiling reflection, a difference which was reduced slightly with the inclusion of the ceiling reflection. Excluding the direct sound (as is often done for common stage parameters) reduced the difference between occupied and empty in some cases, but even with direct sound excluded significant differences between occupied and empty were observed for 500 Hz and 1000 Hz (between 1–5 dB). The effect of the orchestra above 250 Hz appeared to be dependent on the source-receiver path and stage enclosure size, and this highlights the difficulty with applying a correction to empty stage measurements to account for the orchestra, as found by others [Dammerud, 2009, Wenmaekers et al., 2016]. Additionally, other factors will affect the exact findings, for example the investigation has not considered the impact of risers. Overall, the results from the BEM model of a chamber orchestra demonstrate the effect of a chamber orchestra on on-stage sound fields, but cannot easily be used to correct for the presence of a chamber orchestra, and cannot be considered universal as results depend on the source-receiver path through the orchestra and exact stage configuration (i.e. use of risers and arrangement of musicians).

The auditorium measurements agree well with the BEM model results, and confirm that these differences could be found over a 0–50 ms window in an actual hall. The auditorium measurements also show that the higher frequencies (2–4 kHz) are attenuated as much (or slightly more) than the 1 kHz octave band (see Figure 4.10). The BEM model only considered the equivalent of 0–50 ms as only first-order enclosure reflections were considered. Some commonly used stage parameters consider early sound up to 100 ms, however the auditorium measurements indicate that the difference between occupied and empty mostly occurs over 0–50 ms: $\mathrm{SWC}_{\text{occ. - empty}}$ after 50 ms is almost constant, indicating no further change between the occupied condition and empty condition (see Figure 4.10). The results of the BEM study indicate that a chamber orchestra on stage will mostly affect the early time period, which implies parameters assessing late sound (i.e. after 100 ms) on stage are still valid. For parameters assessing early sound on stage occupied stage measurements could be helpful to assess the exact interaction between the space and the orchestra, however in most cases will not be practical. For a chamber orchestra, empty stage measurements then appear to the be the most reasonable alternative (since a standing chamber orchestra does not use chairs and since clearing a reasonable space around source and receiver results in close to the empty stage case anyway).

First-order stage reflections from the enclosure were investigated individually, showing that the angle of the sound path relative to the orchestra affected the results. Significant attenuation occurs for the direct sound, floor reflection, and side wall reflections; the ceiling reflection is not significantly attenuated by the orchestra.

The lack of ceiling attenuation (from the ensemble) produces strong comb filtering (if the ceiling reflection is specular). This highlights the possible positive role for scattering in reflective surfaces above stages. It also appears that the presence of the orchestra can reduce or remove significant comb filtering for the lateral first-order reflections. Work by others with symphony orchestras on stage has highlighted that discrete early reflections can cause colouration, and also that empty stage measurements are not necessarily a realistic representation of actual on-stage sound fields with the orchestra present, in terms of both timbre and ensemble [Halmrast, 2000]. This work has yielded similar findings for a smaller chamber orchestra.

Previous studies have demonstrated the importance of lateral reflections on stage for ensemble playing and noted that overhead reflectors cannot compensate for a lack of early lateral energy from side walls [Dammerud et al., 2011, Guthrie, 2014]. Others have suggested tilting the top section of side walls to provide unattenuated lateral reflections [Gade, 2001, Dammerud et al., 2011]. In this study, the effect of the orchestra with incrementally varying elevation angle of an arriving reflection from the left was investigated for Case 1. This analysis found that for 500 and 1000 Hz octave bands attenuation by the orchestra is reduced as the angle of arrival moves away from horizontal, whereas for 250 Hz and below the results did not depend on angle. For this case tilting the sidewall by 30° from vertical largely removed the effect of the orchestra.

This study focused on a standing chamber orchestra, a playing group which has not been studied in this way previously. The BEM model showed realistic and meaningful results, however the standing orchestra required 1.5 m source-receiver height, which makes these results difficult to compare directly to work by others who used 1 or 1.2 m heights due to the very different interference frequencies [Dammerud and Barron, 2010, Wenmaekers et al., 2016].

4.5 Conclusion

This chapter has focused on analysing the effect of a chamber orchestra on on-stage sound fields, and has shown that even for a relatively small chamber orchestra on stage there is significant attenuation at some frequencies. This study examined both attenuation of direct sound and of the first-order reflections from a stage enclosure. The ceiling reflections were not significantly affected by the orchestra. For the other first-order reflections attenuation was found to be minimal at 125 Hz. However, at 250 Hz and 500 Hz the attenuation was greater, but also more dependent on the source-receiver distance (due to the destructive inference between direct sound and floor reflection). The first-order reflections from the stage enclosure at 1000 Hz were often attenuated by 2–5 dB without including the unobstructed ceiling reflection, and slightly less when the unobstructed ceiling reflection was included. Additionally a tilted side wall case was studied, which showed at the 500 and 1000 Hz octaves lateral attenuation was significantly reduced when tilting the sidewall by 30° from vertical.

Chapter 5

Stage acoustic measurements in Australian concert halls

5.1 Introduction

This chapter details the acoustic stage measurements conducted on stage and in the stalls of 15 auditoria in Australia. The auditoria measured were all subjectively assessed by musicians (as outlined in Chapter 3). The auditorium measurements presented in this chapter are separated based on the surveying datasets. First, eight auditoria are presented which were assessed by the Australian Chamber Orchestra (ACO). Second, two auditoria are presented which were assessed exclusively by chamber ensembles (note that chamber ensembles also assessed auditoria measured as part of the ACO dataset). Last, five auditoria were measured which were assessed by ACO2 (note one auditoria was also assessed by a chamber ensemble).

To objectively assess acoustic conditions on stage for musicians it is most common to use an omnidirectional source and omnidirectional receiver and record impulse response measurements from which stage parameters can be derived, such as those defined in the standard ISO-3382-1 [2009]. The standard specifies that measurements may be made on stage with chairs and music stands present, however with any stage furniture within a 2 m distance of either the source or microphone removed. For a chamber orchestra set up on stage a 2 m distance around the source and the receiver includes the majority of the area in which the orchestra would play. Gade [1992] suggests for a smaller orchestra or ensemble empty stage measurements are appropriate. Additionally, the orchestras investigated in this study played standing (with the exception of cello players), making the use of chairs on stage unnecessary. For these reasons measurements conducted on unoccupied stages were more suitable than measurements conducted with stage furniture present. Past studies have indicated that for a symphony orchestra the most realistic stage measurements will be achieved by including the orchestra on stage during the measurements [Halmrast, 2000, Dammerud and Barron, 2010, Wenmaekers et al., 2016]. The analysis in Chapter 4 confirmed that the presence of a chamber orchestra affects results, however due to expense and time, stage measurements with a full orchestra present have rarely been obtained in past studies and were not attempted for the in situ stage measurements in this work. Therefore in this chapter stage measurements conducted in situ on empty stages are presented. The audience area was also unoccupied during stage measurements, as in other studies involving detailed acoustic measurements on stage. The presence of an audience affects acoustic parameters, particularly those used to assess late or reverberant sound. However in purpose-built halls upholstered seats are designed to behave similar acoustically whether occupied and unoccupied.

The measurements in this study differ from previous measurements conducted in other major studies of stage acoustics (such as by Gade [1989c] and Dammerud [2009]) as they were conducted using a 32 channel spherical microphone array, from which information about the directionality of on-stage sound fields can be derived. The directionality of on-stage sound fields has been noted as subjectively important to musicians in past work. Dammerud [2009] inferred this indirectly by comparing musicians' preferences and ratios of stage geometry; a preference for narrow and high stage enclosures was noted. Guthrie [2014] found this directly using a 16 channel spherical microphone array for measurements on stages, and then conducting auralisation with musicians in a laboratory. Guthrie [2014] defined a spatial parameter called LQ_{7-40} Top/Sides, which compared very early sound energy from above to that from the sides. A preference for lower values of LQ_{7-40} Top/Sides was noted, indicating a preference for more energy from the sides and less from above. This agrees with laboratory work by Domínguez [2008] who found a preference for close lateral reflections and far ceiling reflections.

In this dissertation a spatial parameter has also been defined to compare early sound energy from 'above' to from the 'sides' on stage, in line with this past work. In addition to this Top/Sides parameter, another spatially defined parameter has been investigated comparing sound energy from 'above' to from the 'sides and back'. This was investigated because, depending on their orientation in relation to the side walls, musicians may not distinguish strictly between energy from the 'sides' and from the 'back' on stage. Energy from the 'front' does not need to be considered as on stage there are normally no early reflections from this direction. The spatial analysis of on-stage sound fields is discussed further in Section 5.2.

As well as spatial parameters to assess stage acoustics for musicians, the traditional omnidirectional parameters have been considered including: ST_{early}, ST_{late}, T_{30}, EDT, G_{7-50}, G_e (G_{0-80}) and G_l ($G_{80-\infty}$). These parameters, or a subset of these parameters, have been used intensively in past studies of stage acoustics [Gade, 1989c, Cederlöf, 2006, Berntson and Andersson, 2007, Astolfi and Giovannini, 2007, Dammerud, 2009, Lautenbach and Vercammen, 2013]. These parameters, and their definitions, were discussed in Section 2.3.1.

In this chapter the stage measurements are explored in depth. Consideration is given to variation in stage parameters with location on stage and subsequently the validity of stage averages. For 1 m measurements, the stage average is generally found to be valid when considering the area on stage used by a chamber orchestra. In some auditoria multiple acoustic settings were tested and stage parameters for these different configurations are given. The relationship between acoustic stage parameters and architectural measures are also studied. This demonstrates which stage parameters relate closely to easily measured architectural measures, such as stage enclosure dimensions. These investigations show how stage parameters vary depending on various factors such as position on stage, stage dimensions and stage settings. In this chapter comparisons are not made to subjective musicians' ratings. The relationships between subjective data and stage parameters are discussed in Chapter 6.

5.2 Spatial analysis of on-stage sound fields

In this section the spatial analysis of on-stage sound fields, undertaken with the spherical microphone array the Eigenmike, is presented. As noted above, recent studies have indicated the directionality of on-stage sound fields may be subjectively relevant to musicians playing on stage [Domínguez, 2008, Dammerud, 2009, Guthrie, 2014], and the purpose of this analysis is to allow parameters designed to assess on-stage sound field directionality to be defined and explored. The spatial regions and spatial filtering procedure used in this analysis are discussed in Section 5.2.1. Two spatial parameters are defined in Section 5.2.2: one which assesses energy from above relative to energy from the sides on stage, and one to assess energy

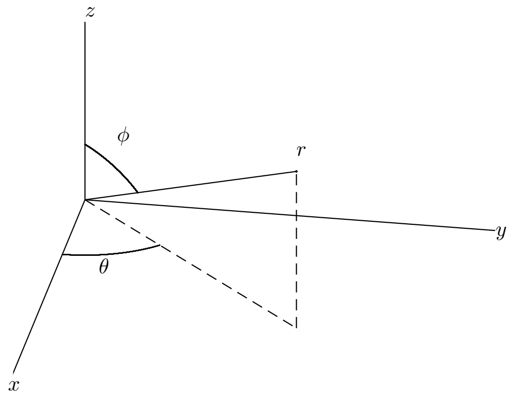


Figure 5.1: Cartesian and spherical coordinates used in the analysis.The x axis points towards the audience (front); θ is defined as the angle towards the y axis from the x axis, and ϕ is defined as the angle downwards from the z axis towards the xy plane.

from above relative to from horizontal (i.e. sides and back). Then a discussion around the time interval selected for the spatial parameters is given in Section 5.2.3. Finally, characteristics of the spherical microphone array are discussed in Section 5.2.4.

5.2.1 Definitions of spatial regions and spatial filtering procedure

This section describes the spatial regions, and spatial filtering procedure using higher order Ambsonics, used later to define spatial parameters. A background to Higher Order Ambisonics is outlined in Appendix F. The spatial regions in this work are designated as 'top', 'bottom', 'left', 'right', 'front'(down-stage) and 'back'(up-stage). These regions are defined as the solid angles subtended by the faces of a cube centered at the origin and aligned with the x, y and z axes defined in Figure 5.1. For example, if sound arrives through the top of the cube it is assigned to the 'top region'. The cube is oriented such that the 'front' faces towards the audience and 'top' faces towards the stage ceiling. Using spherical coordinates (defined in Figure 5.1), the regions can be projected onto the (θ, ϕ) space, as shown in Figure 5.2.

Spatial filtering is performed to capture the sound energy arriving from each region. To achieve the desired spatial filtering first the 32 physical channels corresponding to the individual microphones must be decoded into the Ambisonic channels. For N_O^{th} order there will be $(N_O + 1)^2$ Ambisonic channels and this number must be less than the number of

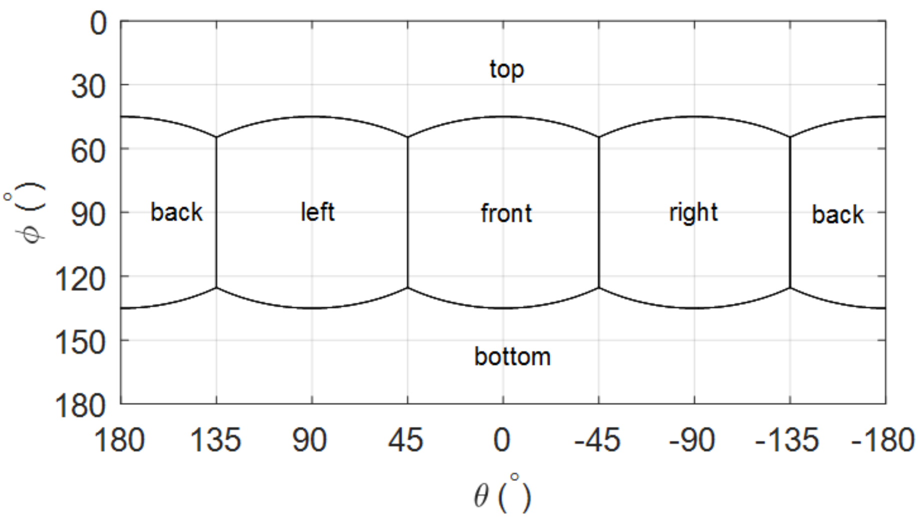


Figure 5.2: The spatial regions are defined as the faces of a cube centered at the origin with edges parallel to the x, y and z axes projected onto the (θ,ϕ) space; left, right, front, back, top and bottom are defined as shown.

microphones in order to obtain a unique Ambisonic decoding. In this work we have limited the analysis to 2$^{\text{nd}}$ order ($N_O = 2$), which corresponds to nine channels. The rationale for using 2$^{\text{nd}}$ order, given that 4$^{\text{th}}$ order is possible, is presented in Section 5.2.4.

Using 2$^{\text{nd}}$ order analysis to combine the nine Ambisonic channels with appropriate weights, as determined by the method outlined in Appendix F, energy from any desired region (targeted at a single direction or a solid angle) can be captured. With infinite order this can be achieved perfectly, but if the series is truncated to a finite order the representation will of course be an approximation. Appropriate weightings must be applied to the higher-order Ambisonics (HOA) channels to give as close as possible a unit signal strength within the desired region and zero signal strength outside the desired region.

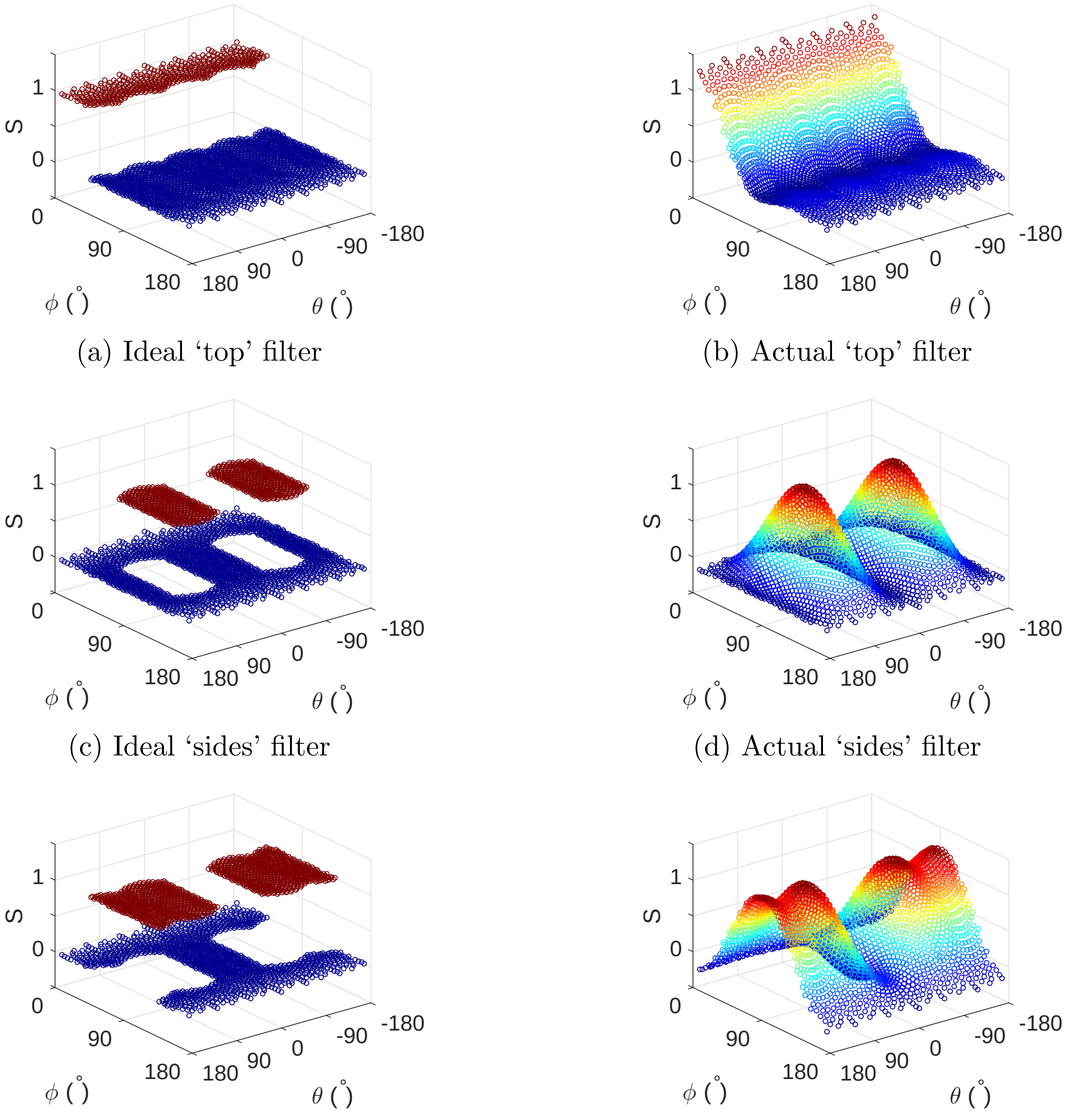
Three spatial filters were created. The spatial filters are discussed here, however the reasoning behind creating these three spatial filters is discussed in Section 5.2.2. The first was a spatial filter to accept the signal from the 'top' region (while rejecting all other regions). A visual representation of the ideal top filter, using 3002 points very nearly equally spaced over the sphere, is shown in Figure 5.3a. The second was a spatial filter to accept the signal from both the 'left' and 'right' region (while rejecting all other regions), and the 'left' and 'right' regions together will be referred to as 'sides'. A visual representation of the ideal sides filter, using 3002 points very nearly equally spaced over the sphere, is shown in Figure 5.3c.

The third was a spatial filter to accept the signal from both the 'left', 'right' and 'back' regions (while rejecting all other regions), and the 'left', 'right' and 'back' regions together will be referred to as 'horizontal'. A visual representation of the ideal horizontal filter, using 3002 points very nearly equally spaced over the sphere, is shown in Figure 5.3e. In the ideal case these spatial filters would provide complete signal rejection from all the undesired regions ($s_k = 0$), but complete signal acceptance within the desired region ($s_k = 1$). When interpreting Figures 5.3a, 5.3c and 5.3e recall that the regions have been defined based on the faces of a cube in spherical polar coordinates, refer to Figure 5.2. The weights $\{w\}$ to be applied to the spherical harmonic channels were determined according to the procedure in Appendix F to create the best spatial filter achievable using 2$^{\text{nd}}$ order Ambisonics. In Figure 5.3b a visual representation of the actual spatial filter for 'top' is shown, in Figure 5.3b a visual representation of the actual spatial filter for 'sides' is shown and in Figure 5.3f a visual representation of the actual spatial filter for 'horizontal' is shown. Figure 5.3 provides a comparison of the ideal case, where the signal within the desired regions can be isolated perfectly, and the actual case which is the best signal acceptance/rejection that can be achieved with 2$^{\text{nd}}$ order spherical harmonics. By the reciprocity principle a hypothetical sound field of the form of Figure 5.3a will be detected in 2$^{\text{nd}}$ order Ambisonic form as in Figure 5.3b, i.e. it will not be detected uniformly over the desired region and there will be 'leakage' as sound appears to come from adjacent regions.

5.2.2 Defining Top/Sides and Top/Horizontal spatial energy ratio parameters

In this section two spatially-defined acoustic stage parameters are defined using the spatial filters discussed in Section 5.2.1.

The use of spherical microphone arrays, and higher order Ambisonics (HOA), to investigate stage acoustics is a relatively new field of study. However, some previous work has been undertaken to adapt existing stage parameters to 'directional' versions [Cabrera et al., 2010, Guthrie, 2014]. Cabrera et al. [2010] used a 1$^{\text{st}}$ order microphone analysis of stage support to examine the directional acoustic effect of a stage set on a spoken word theatre stage, using cardioid beamforming in the six axes (top, bottom, left, right, front, back), and simply adapted the conventional stage support parameters for directional analysis. Guthrie [2014] developed the concept of spatial analysis on stages further by not only redefining many of



(a) Ideal 'top' filter

(b) Actual 'top' filter

(c) Ideal 'sides' filter

(d) Actual 'sides' filter

(e) Ideal 'horizontal' filter

(f) Actual 'horizontal' filter

Figure 5.3: The ideal and actual spatial filters for 'top', 'sides' and 'horizontal'.

the common stage acoustic parameters (e.g. the ST measures, LQ_{7-40}, G_e, G_l) based on directional regions, but also as ratios between directional regions. However, Guthrie used slightly different definitions for spatial regions to those used in this study, and additionally a different method for spatial filtering. Guthrie steered beams in 21 evenly-spaced directions (2^{nd} order beams that overlapped at half power points), and summed the energy in each region ('top' and 'sides') to calculate the LQ_{7-40} Top/Sides. The equation for LQ_{7-40} Top/Sides was previously given in Equation 2.16 (see Section 2.3.2). Guthrie only examined this parameter at the 1 kHz octave band. Guthrie [2014] found in a laboratory study that a spatial ratio of LQ_{7-40} from Top/Sides was relevant for musician playing in ensemble conditions (lower values were preferred).

In this study the first spatial parameter explored is a Top/Sides ratio, similar to the Top/Sides parameters used by Guthrie, but with some changes to the integration limits, the exact form of the parameter, and with a different approach to combining Ambisonics signals to create optimal spatial region beams. For the Top/Sides parameter in this study a lower integration time limit of 20 ms was selected; this was based on an investigation of the on-stage impulse responses, which found this was an appropriate time to remove the direct sound and floor reflection, but was before the occurrence of any of the stage enclosure reflections. It was crucial to remove the direct sound as it is significantly higher in magnitude than the stage reflections and thus if it was included any differences in enclosure reflections between stages could not easily be observed. The upper integration time limit of 50 ms was selected to capture 'early' reflections. The choice of this time interval for the spatial parameter is discussed further in Section 5.2.3. This spatial ratio of 'top' relative to 'sides' has been denoted as TS_{20-50} and defined as

$$TS_{20-50} = 10 \log \frac{\int_{20\,\text{ms}}^{50\,\text{ms}} p_{\text{top}}^2(t).dt}{\int_{20\,\text{ms}}^{50\,\text{ms}} (p_{\text{left}}(t) + p_{\text{right}}(t))^2.dt}. \tag{5.1}$$

The numerator of Equation 5.1 is the signal spatially filtered using the 'top' filter shown in Figure 5.3b, and the denominator is the signal spatially filtered using the 'sides' filter shown in Figure 5.3d. The TS_{20-50} parameter was calculated from 1 m source-receiver measurements. The on-stage measurement procedure is discussed in Section 5.3.1. The method of averaging 1 m measurements on-stage is in line with the procedure used for the ST parameters. It may also be of interest to investigate the 'across-stage' measurements (with larger source-receiver distances) when considering ensemble playing (across-stage results have not been included in the present work).

In addition to TS_{20-50}, a second spatial stage parameter has been explored, which is defined in the same manner, but includes 'back' reflections as well 'sides' in the denominator. Thus the parameter is a ratio of sound energy from 'top' to sound energy from 'horizontal plane' (i.e. 'left', 'right' and 'back'), and will be denoted TH_{20-50}. The sound energy from the 'front' region has been neglected as it will point towards the audience area, and over the time interval investigated (20–50 ms) there will be negligible reflections from this region. Thus TH_{20-50} can be defined as

$$TH_{20-50} = 10 \log \frac{\int_{20\,\mathrm{ms}}^{50\,\mathrm{ms}} p_{\mathrm{top}}^2(t).dt}{\int_{20\,\mathrm{ms}}^{50\,\mathrm{ms}} (p_{\mathrm{left}}(t) + p_{\mathrm{right}}(t) + p_{\mathrm{back}}(t))^2.dt}. \tag{5.2}$$

The numerator of Equation 5.2 is the signal spatially filtered using the 'top' filter shown in Figure 5.3b, and the denominator is the signal spatially filtered using the 'horizontal' filter shown in Figure 5.3f. This parameter has been investigated because for musicians on stage the effect of side and back reflections can be assumed to be similar, particularly since musicians are orientated variously on stage. In the audience area the special status of lateral reflections is more intuitive since audiences members are orientated forwards (towards the stage). Musicians will usually be orientated inwards, such as towards a conductor or concertmaster location, for improved communication visually and acoustically.

5.2.3 'Early' time interval for Top/Sides and Top/Horizontal ratios

This section discusses the choice of 50 ms to isolate 'early' sound energy for the spatial stage parameters. In past studies various time intervals have been used to define 'early' sound on stage. Gade [1989c] used 20–100 ms when defining the commonly used stage parameter ST_{early}. Dammerud [2009] used 0–80 ms for the stage parameter G_e, and also used 7–50 ms for the parameter G_{7-50}. van Den Braak and van Luxemburg [2008] used 7–40 ms for the parameter LQ_{7-40}, which was originally proposed to assess stage acoustics for conductors but was shown to also relate to musicians' preferences. A later study of this parameter found the interval 7–40 ms was more easily able to distinguish between well-liked and disliked halls than 7–80 ms [van Luxemburg et al., 2010]. Guthrie [2014] used a spatially-defined version of LQ_{7-40} to compare energy from above to energy from the sides on stage, and found a correlation with musicians' preferences.

From past work it appears that the direction of 'very early' (i.e. earlier than 100 ms) sound energy on stage is most relevant to musicians preferences [Guthrie, 2014]. In the present study, 50 ms was selected to isolate 'very early' sound energy on stage. Visually inspecting the impulse responses confirmed that for the stage enclosures in this study it was common for early first-order stage reflections to arrive between 40–50 ms, meaning abrupt changes to TS and TH with a change to the upper integration between 40–50 ms. It is unlikely that there is a significant difference subjectively over this 10 ms window, meaning an upper integration limit of 50 ms appears more appropriate. Also, noting that the abrupt changes to TS and TH were not observed between 50–60 ms. Overall, it is hypothesised that the direction of these strong first-order reflections are subjectively relevant to musicians, and 20–50 ms has been used to test this with spatially-defined acoustic stage parameters.

When exploring the spatial distribution of sound on stage we are interested in both the strength and timing of first-order reflections from above and from the sides. Within the scope of this study using in situ measurements and surveying it is not possible to fully explore this. In the future laboratory work could test the relative importance of strength and timing further.

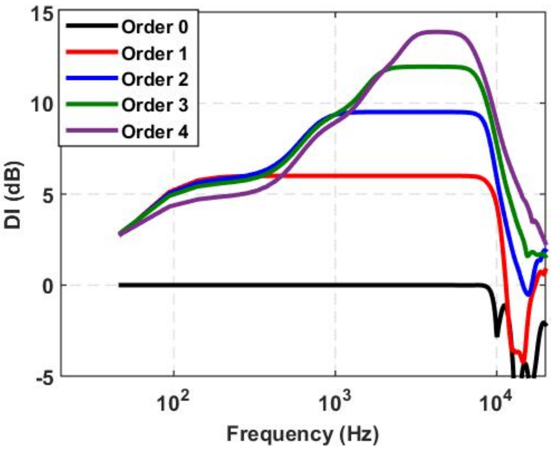
5.2.4 Spherical microphone characteristics

A spherical microphone array may be used to encode a sound field into its spherical harmonic components, and in this work the spherical microphone array used was the Eigenmike, with 32 transducers. The performance of a spherical microphone array depends on how accurately the HOA signals can be retrieved from the microphone signals; several sources of error limit this performance and dictate the operational frequency range of the microphone. For a given HOA order the performance of the spherical microphone array depends on the number of transducers, the distance between the transducers relative to the wavelength, the transducer noise and the positioning accuracy of the transducer [Miranda et al., 2013].

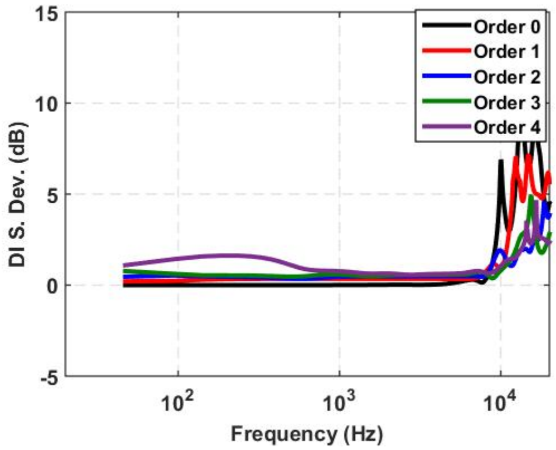
A particularly useful indicator of the beamforming performance of a spherical microphone array is the directivity index (DI). The DI considers spatial aliasing, measurement noise, and microphone placement errors [Parthy et al., 2011]. Previous work on microphone arrays has shown that the DI curves can clearly define the bandwidth of operation, which is the frequency range with constant and maximum DI (for a given HOA order) [Parthy et al., 2011].

The Directivity Index (DI) of the microphone array has been calculated across the frequencies of interest. The DI has been calculated using a similar method as the one proposed by Parthy et al. [2011]. The simulations included the radius and capsule placement of the Eigenmike. A microphone noise floor of -60 dB below its clipping level was assumed. This is a very conservative figure for high quality microphone pre-amps and capsules. No microphone placement error was included since it is assumed that the manufacturing processes of this particular microphone presents small possibility for construction inaccuracies. To generate the DI curves, maximum directivity beams for each encodable HOA order were calculated. Beams were created pointing at 585 locations evenly distributed around a sphere and sources evenly distributed around the same locations. The DI of the simulated beam was calculated based on the focal point of the beam (Figure 5.4a). Additionally, standard deviation of the directivity for each frequency was calculated (Figure 5.4b). This allows us to understand differences in directivity that might occur based on the focal direction of the beam.

From Figure 5.4a, 2$^{\text{nd}}$ order Ambisonics the operational frequency range is roughly 900 Hz–7 kHz; whereas for 3$^{\text{rd}}$ order Ambisonics this range is 2–7 kHz, and for 4$^{\text{th}}$ order Ambisonics the range is 3–6 kHz. While the ability to resolve sound direction (DI) improves with higher order, it does so over progressively narrower frequency ranges. The results presented in this work are based on 2$^{\text{nd}}$ order coding. The usual frequency range presented for stage parameters is 250–2000 Hz, and in this study results will be presented for 250 Hz and 500 Hz octave bands, despite these being outside the optimum range for directivity based on Figure 5.4a. Interestingly though, 2$^{\text{nd}}$ order and 4$^{\text{th}}$ order analyses gave very similar results, which provided confidence in the 2$^{\text{nd}}$ order results presented in this work.



(a) Directivity index (DI) versus frequency for the Eigenmike, varying with HOA order N_O.



(b) Directivity index (DI) standard deviations (S. Dev.) for directivity versus frequency for the Eigenmike, varying with HOA order N_O.

Figure 5.4: Microphone characteristics for Eigenmike. The code used to produce these figures has been implemented in AARAE by Luis Miranda.

5.3 Measurements in auditoria assessed by ACO

Acoustic measurements were conducted on stage and in the stalls areas of eight purpose-built auditoria, which were visited by the ACO during a tour in June 2015. The eight purpose-built auditoria measured are given in Table 5.1. In the following sections the auditoria are given in order of preference, as rated by ACO, where PH was the highest-rated hall and WH was the lowest-rated hall.

Table 5.1: Auditoria assessed by ACO

Auditorium	City	Auditorium Identifier
Perth Concert Hall	Perth	PH
Adelaide Town Hall	Adelaide	AH
City Recital Hall, Angel Place	Sydney	AP
Llewellyn Concert Hall	Canberra	LH
Hamer Hall	Melbourne	HH
Sydney Opera House Auditorium	Sydney	SO
Queensland Performing Arts Centre Concert Hall	Brisbane	QC
Wollongong Town Hall	Wollongong	WH

The stages are shown in Figure 5.5, and additional images of the auditoria are provided in Appendix G. The dimensions for the auditoria are given in Table 5.2. Stage diagrams are also included in Appendix H for the auditoria on the ACO tour, as well the other auditoria

Table 5.2: Auditorium and stage dimensions and architectural measures for auditoria visited by ACO, where W is width to side reflecting surfaces, H is the height from stage to above reflecting surfaces and D is the stage depth.

	Room volume (m^3)[a]	Stage area (m^2)[a]	Stage width front (m)	Height above stage (m)	Stage depth (m)	W (m)	H (m)	D (m)	H/W	$H/\sqrt{D \cdot W}$
PH	18800	180	18.2	16.5	11.1	18.2	16.5	11.1	0.91	1.16
AH	9800	120	17	11.4	7.3	20.2	11.4	7.3	0.56	0.94
AP[b]	10600	100	13	12	9.2	13	12	9.2	0.92	1.10
LH	28500	140	19.5	9.8	8	19.5	9.8	8	0.50	0.78
HH	27000	120	19.1	9.5	7.3	19.1	9.5	7.3	0.50	0.80
SO	26400	200	20.5	22 (9)[c]	11.5	20.5	9	11.5	0.44	0.59
QC	22400	235	16.4	17.3	14.7	16.4	17.3	14.7	1.05	1.11
WH	13000	90	12	5.8	7.1	12	5.8	7.1	0.48	0.63

[a] Room volumes and stage areas have generally been estimated from auditorium dimensions (approximate only)
[b] 2 m stage extension in place
[c] Average height of suspended reflectors

measured. Three additional dimensions are also considered: W, H and D, where W is width to side reflecting surfaces (at the front of the stage), H is the height from stage to above reflecting surfaces and D is the stage depth, and also given in Table 5.2. Note that since W is the width to side reflecting surfaces it is not the same as the dimension 'stage width front', since in some auditoria there is no stage enclosure (and in these cases W may actually be the auditorium width). In most cases H is the ceiling height, however if there are lower reflecting surfaces (i.e. over head reflectors) this height is used. In addition to H, D and W, two ratios have been considered: H/W and $H/\sqrt{D \cdot W}$. Note that $D \cdot W$ is a simple stage area (units m^2), and by taking the square root the ratio $H/\sqrt{D \cdot W}$ is dimensionless. In a simplified manner, H/W considers vertical sound energy compared to lateral sound energy on stage (similar to the proposed spatial acoustic parameter TS_{20-50}). In a simplified manner, $H/\sqrt{D \cdot W}$ consider vertical sound energy compared to horizontal sound energy on stage (similar to the proposed spatial acoustic parameter TH_{20-50}).

5.3.1 Measurement procedure in ACO auditoria

Measurements were undertaken on stage in the eight auditoria assessed by ACO using the same equipment and measurement procedure. The source used was a Brüel&Kjær omnidirectional loudspeaker type 4295 with a Brüel&Kjær power amplifier type 2734. The receiver was a 32 channel spherical microphone array type Eigenmike 32. The source and receiver are shown in Figure 5.6. Computer software and an audio interface were also used in the measurements: AARAE (release 6) and Fireface UCX interface. AARAE is Matlab-hosted software for audio and acoustic measurement and analysis, developed at the University of Sydney, see Cabrera et al. [2014] for details. Measurements were undertaken on empty stages (without stage furniture). In auditoria where detailed architectural plans are not available stage dimension and auditoria dimensions were recorded.

The centre of the source and receiver were both 1.5 m above the stage floor from all measurements. According to ISO-3382-1 [2009] both source and receiver should be either 1.0 m or 1.5 m from the stage. A source-receiver height of 1.5 m was used because a majority of the orchestra members were standing during the performance, and that the ears of the seated musicians (the cello and double bass players) would likely be higher than 1.0 m as they were on box risers. The on-stage source positions are shown in Figure 5.7 and correspond nominally to the approximate centres of the 1st violin, 2nd violin, viola and cello sections of a typical chamber orchestra; around each source position four 1 m measurements were taken (in positions front, back, left and right relative to the stage orientation). Additionally, across-stage measurements were undertaken between all pair combinations of the four source positions. Across-stage measurements have source-receiver distances between 2.7 m and 6 m. In HH the coordinate system was shifted by 1.5 m in the negative x direction (upstage) due to the unusual curved front of the stage. Measurements with the source on stage (3 m from front of stage on the centreline) and receiver within the stalls area were also conducted.

In four auditoria a modified version of the measurement procedure was also completed with a Brüel&Kjær omnidirectional receiver type 4190. A comparison of omnidirectional stage parameters with the Eigenmike and omnidirectional microphone is in provided in Appendix I.

The acoustic conditions in auditoria were matched to those used by the ACO during their concerts. The settings used for measurements to match ACO settings are outlined in Table 5.3. In AP measurements were undertaken on stage with and without the 2 m stage extension; however, the measurements with the 2 m stage extension in place are presented in Section 5.3.2 as this was the setting used by ACO. A comparison of measurements with and without the stage extension is presented in Section 5.3.5.2. In SO stage measurements were undertaken with the acoustic cloud reflectors at the chamber setting, and also at the highest setting. The measurements with the chamber setting are presented in Section 5.3.2 as this was the setting used by ACO. A comparison of the two settings is discussed in Section 5.3.5.1. In AH a stage extension was in place to match the conditions used by ACO; however, due to availability a slightly smaller stage extension was used compared to the one used by ACO (a 4.9 m stage extension was used by ACO and a 3.7 m stage extension was used during measurements). In auditoria other minor acoustic settings were also matched to those used by the ACO, such as the position of drapes.

Table 5.3: Adjustable settings used in ACO auditoria

Auditorium Identifier	Setting used for measurements
PH	N/A
AH	Stage extension in place (3.7 m)
AP	Stage extension in place (2 m)
LH	Adjustable backwall at 8 m from front of stage
HH	Adjustable acoustic ceiling and rear lift in ACO positions
SO	Cloud reflectors at chamber setting (approximately 9 m from stage)
QC	N/A
WH	Stage extension in place (1.9 m)

5.3.2 Omnidirectional stage parameter results

Traditional stage parameters were derived using the 1st Ambisonics channel (the 0th order or omnidirectional channel). An implementation to compute the Ambisonic channels from the raw data obtained from the Eigenmike is included in AARAE (as discussed in Appendix F), see Cabrera et al. [2014] for further details. In four auditoria both the Eigenmike and Brüel&Kjær omnidirectional microphone type 4190 were used in order to assess the agreement between the Eigenmike and an industry-standard precision omnidirectional microphone (these results are given in Appendix I).

The parameters investigated include: ST_{early}, ST_{late}, T_{30}, EDT, G_{7-50}, G_e (G_{0-80}) and G_l ($G_{80-\infty}$). In the following tables and figures the auditoria are plotted from left to right in order of the musicians' most preferred to least preferred auditorium (PH is the most preferred auditorium and WH is the least preferred auditorium).

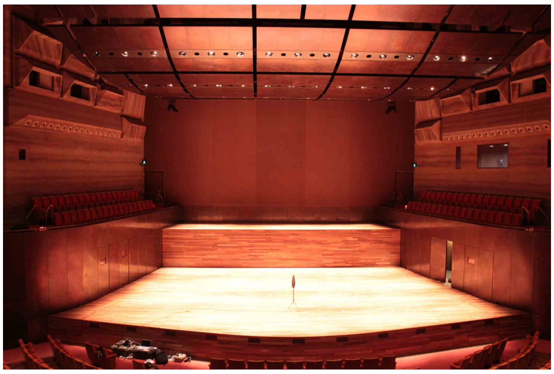
In Figures 5.8 and 5.9 the individual octave bands 250–2000 Hz are presented for ST_{early} and ST_{late} respectively. These figures demonstrate good agreement between these four octave

(a) PH

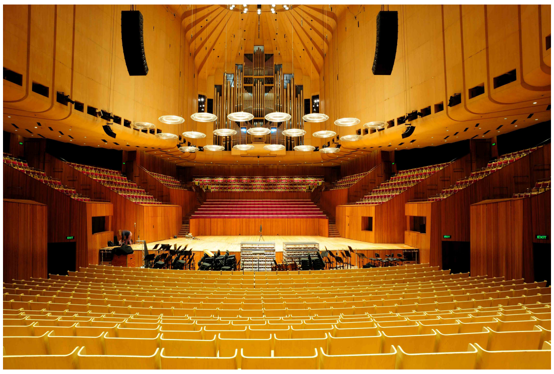
(b) AH

(c) AP

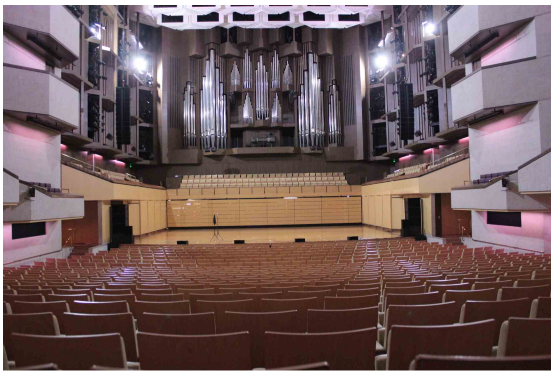
(d) LH



(e) HH



(f) SO

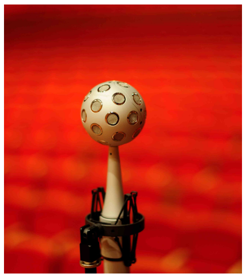


(g) QC

(h) WH

Figure 5.5: Images of auditoria visited by ACO tour during June 2015 tour

(a) Brüel&Kjær omnidirectional loudspeaker



(b) Eigenmike

Figure 5.6: Source and receiver used in auditoria measurements

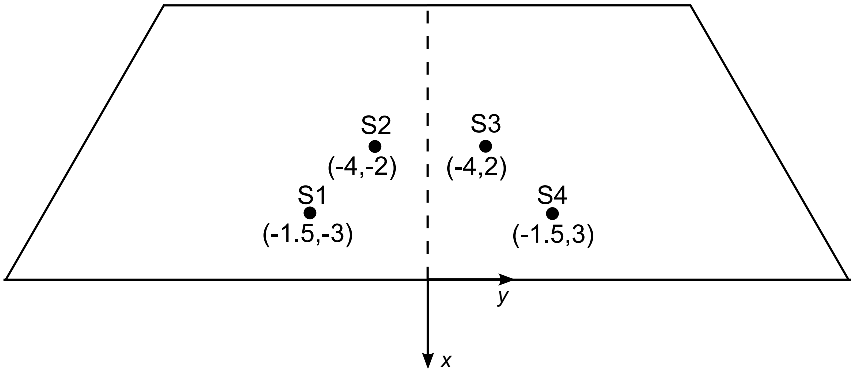
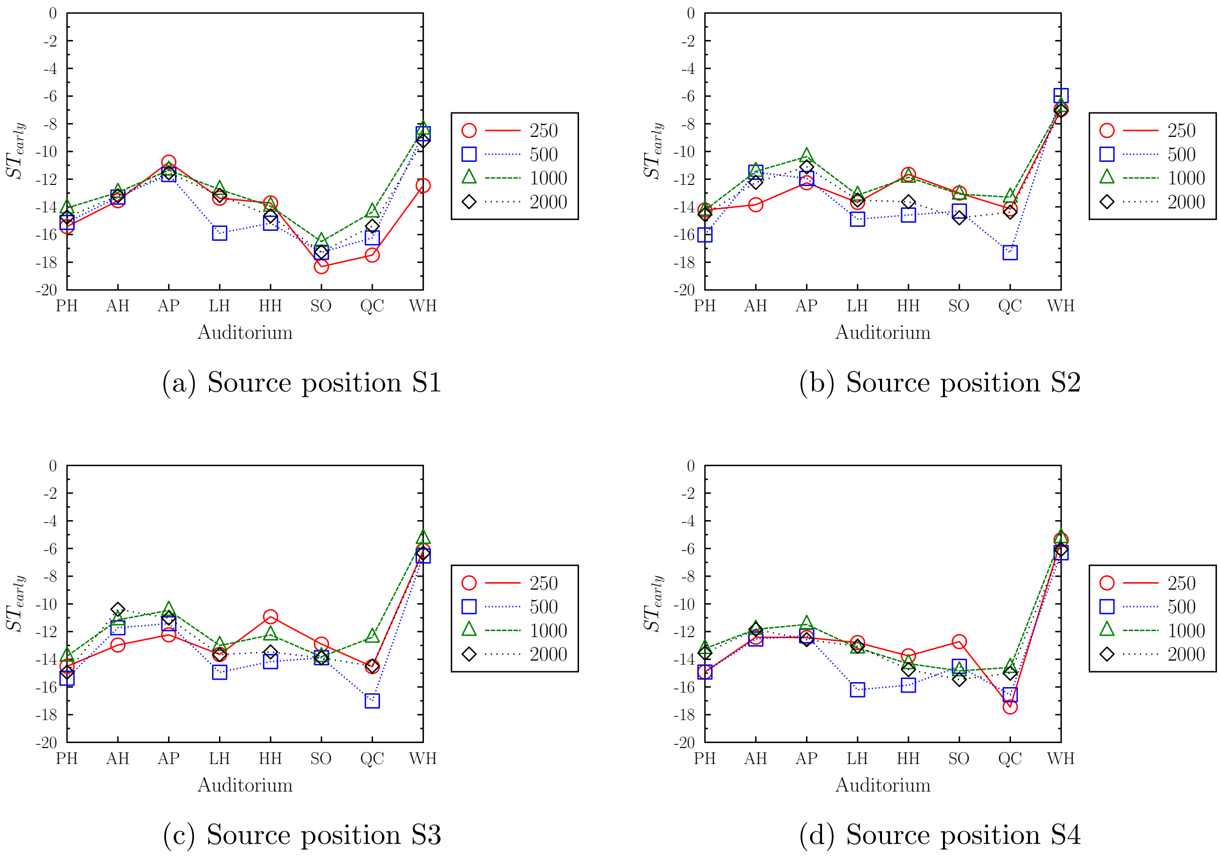


Figure 5.7: The on-stage measurement locations for ACO auditoria. Dimensions in metres. The coordinate system is located at the center front of the stage. Receivers had the same locations for across-stage measurements, and were at positions (1,0), (0,1),(-1,0) and (0,-1) relative to the sources for the 1 m measurements.

bands. In Figure 5.10 the spatial variation of the ST parameters around the stage is presented, and overall the stage average for ST is reasonably indicative of the stage as whole when considering the area of stage used by a chamber orchestra (for 250–2000 Hz arithmetic average). ST_{early} and ST_{late} arithmetically averaged over 250–2000 Hz octave bands and across the four source positions (S1–S4) are presented in Table 5.4 and Figure 5.11. The arithmetic averaging of octaves 250–2000 Hz and various on stage positions is in line with the procedure in ISO-3382-1 [2009]. From these results, the most distinctive auditorium is WH, which has far higher values of ST_{early} and ST_{late} than the other auditoria included in the study.

In Table 5.5 on stage T_{30} at octave bands 250–2000 Hz are given. In Table 5.6 on stage EDT at octave bands 250-2000 Hz are given. T_{30} and EDT were averaged over all across-stage source-receiver pairs. Minimal variation is noted between the halls in terms of on stage T_{30} and EDT, which is expected in this set of purpose-built auditoria.



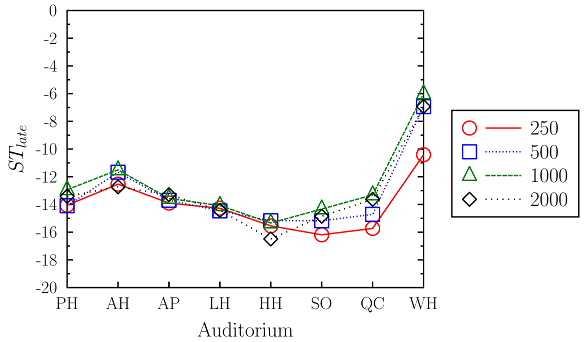
(a) Source position S1

(b) Source position S2

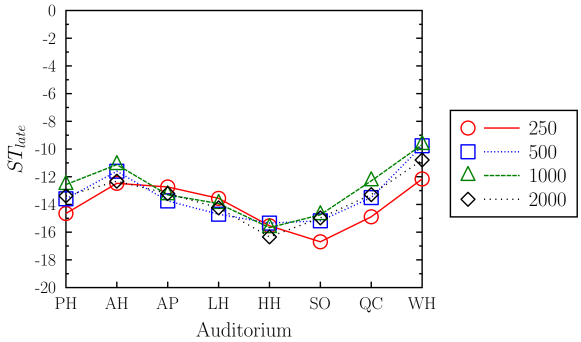
(c) Source position S3

(d) Source position S4

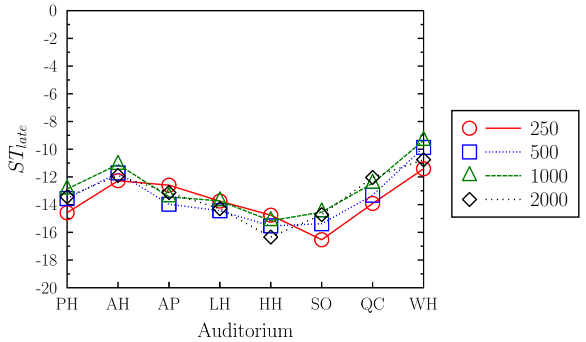
Figure 5.8: ST_{early} (dB) compared to auditorium for 250–2000 Hz octave bands at source positions on stage.



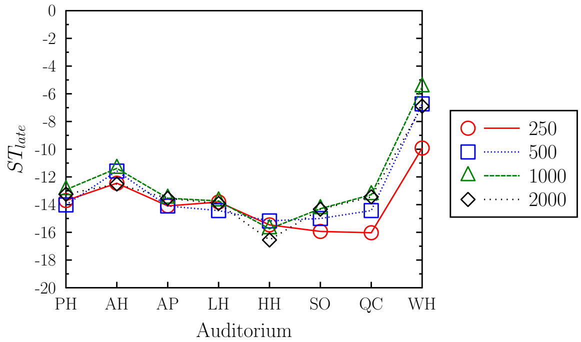
(a) Source position S1



(b) Source position S2

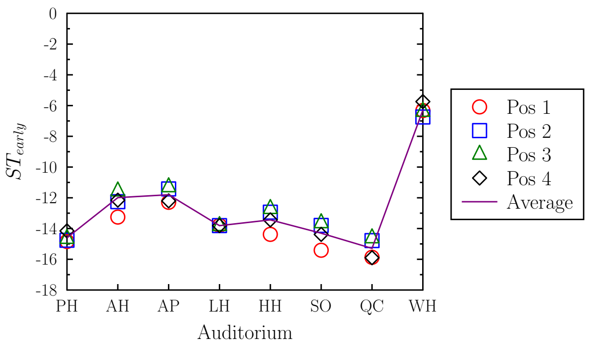


(c) Source position S3

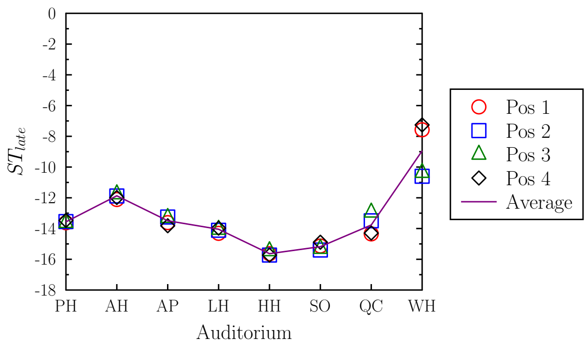


(d) Source position S4

Figure 5.9: ST_{late} (dB) compared to auditorium for 250–2000 Hz octave bands at source positions on stage.



(a) ST_{early}



(b) ST_{late}

Figure 5.10: ST parameters arithmetically averaged over 250-2000 Hz for positions S1–S4 (shown as markers), and finally spatially averaged to give a stage average over 250-2000 Hz (shown as a solid line).

Table 5.4: The ST measures arithmetically averaged over 250–2000 Hz and over the four source positions.

Parameter (dB)	S-R dist. (m)	PH	AH	AP	LH	HH	SO	QC	WH
ST_{early}	1	−14.6	−12.0	−11.8	−13.8	−13.4	−14.3	−15.3	−6.3
ST_{late}	1	−13.6	−11.9	−13.5	−14.1	−15.6	−15.2	−13.8	−9.0

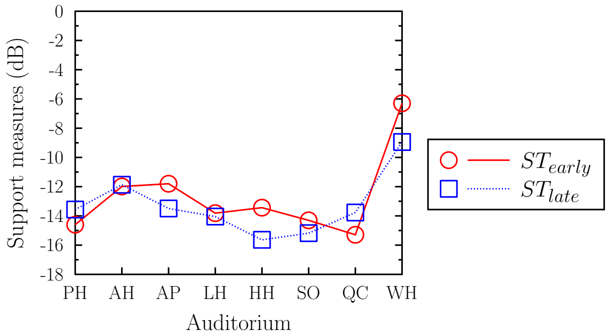


Figure 5.11: Arithmetic average of ST measures with 1 m source-receiver distance over 250–2000 Hz octave bands.

Table 5.5: T_{30} 250–2000 Hz octave bands (average for all across-stage source-receiver pairs).

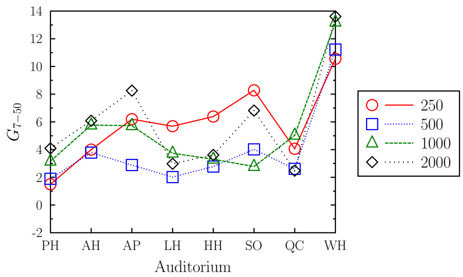
Octave (Hz)	S-R dist. (m)	PH	AH	AP	LH	HH	SO	QC	WH
250	> 2.7	1.76	2.05	1.92	2.07	1.95	1.94	1.98	1.61
500	> 2.7	1.91	2.17	1.81	1.82	1.92	2.06	2.17	2.03
1000	> 2.7	2.06	2.02	1.87	1.91	1.82	2.37	2.26	2.10
2000	> 2.7	1.96	1.79	1.96	1.86	1.57	2.36	2.11	1.71

Table 5.6: EDT 250–2000 Hz octave bands (average for all across-stage source-receiver pairs).

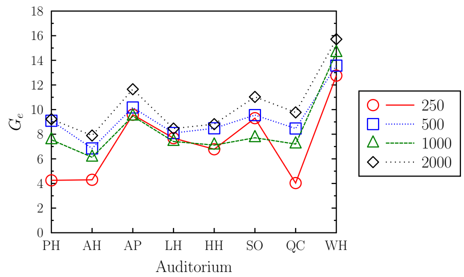
Octave (Hz)	S-R dist. (m)	PH	AH	AP	LH	HH	SO	QC	WH
250	> 2.7	1.31	1.84	1.39	1.71	1.17	0.83	1.07	1.19
500	> 2.7	1.71	2.23	1.41	1.80	1.36	1.35	1.78	1.61
1000	> 2.7	1.70	2.00	1.38	1.63	1.07	1.59	1.77	1.52
2000	> 2.7	1.74	1.83	1.43	1.76	1.21	1.41	1.74	1.26

In Figure 5.12, the sound strength parameters are reported for 250–2000 Hz octave bands for the 5.6 m measurements (i.e. S1–S3 or S2–S4). G_{7-50}, G_e and G_l were notably greater in WH than in the other auditoria in the study. This was also evident in the across-stage measurements with 2.7, 4 and 6 m source-receiver distances (i.e. S1–S2 or S3–S4, S2–S3 and S1–S4 respectively). WH is a relatively small stage, see Table 5.2. Note, the modified versions of sound strength G (G_{7-50}, G_e and G_l) have been power averaged. For reference G_{7-50}, G_e and G_l are the 2.7, 4, 5.6 and 6 m measurements are provided in Appendix J.1.1.

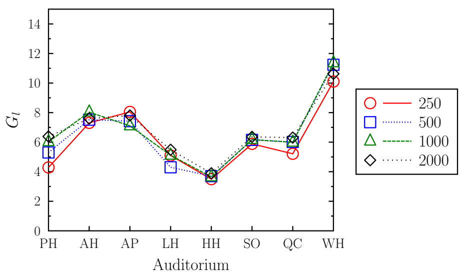
The objective omnidirectional parameters provided in this section are discussed further in comparison to the subjective musicians' responses in Section 6.2.1.



(a) G_{7-50}



(b) G_e



(c) G_l

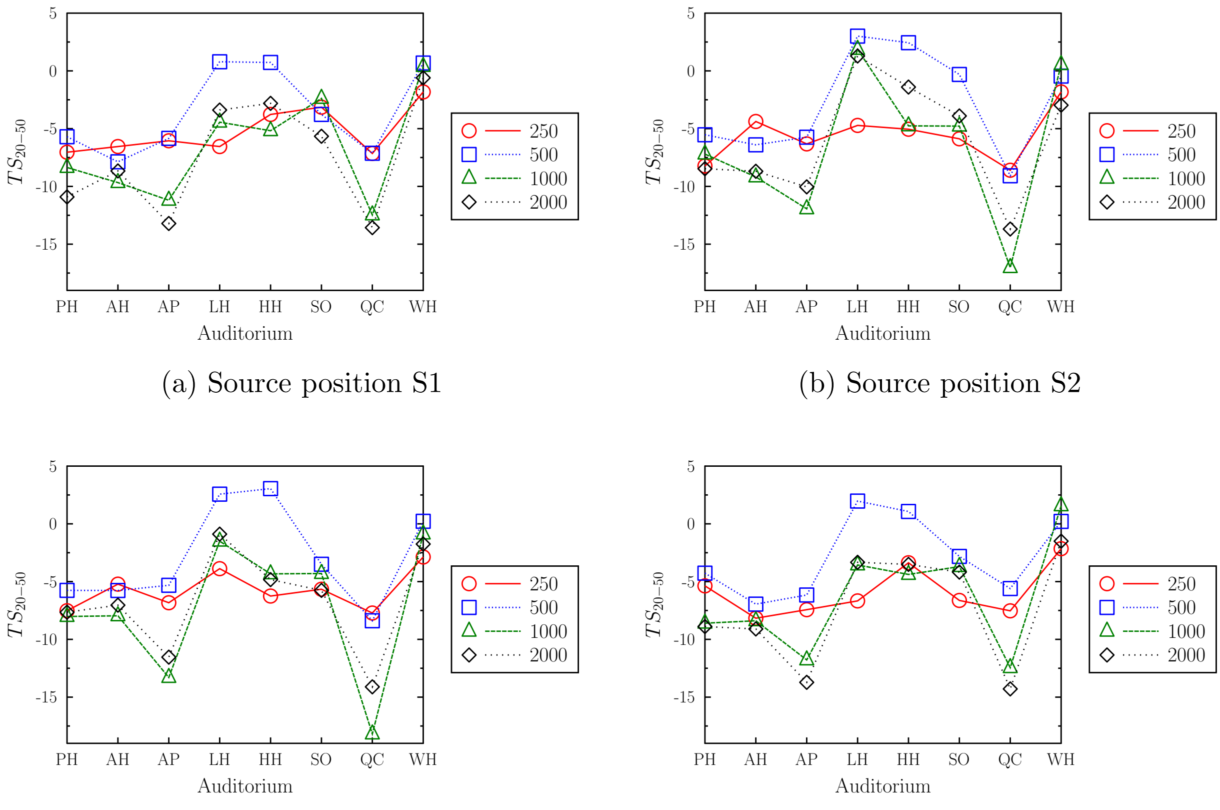
Figure 5.12: Modified sound strength parameters (G_{7-50}, G_e and G_l) for power average of measurements with source-receiver distance 5.6 m and across octave bands 250–2000 Hz.

5.3.3 Spatial stage parameters

In this section spatial stage parameters, which consider the directionality of on-stage sound fields, are presented, including results for the Top/Sides (TS_{20-50}) and Top/Horizontal (TH_{20-50}) ratios. The definition and method for finding these parameters has been discussed in Section 5.2.

Power average TS_{20-50} (dB) for 1 m source-receiver distance at positions S1–S4 are presented in Figure 5.13, for individual octave bands 250–2000 Hz. It is noted that a similar curve is observed at each position on stage. In Figure 5.14 the power average over 250–2000 Hz octave bands is presented at each source position (S1–S4), as well as the power average of the four on-stage positions over the 250–2000 Hz octave bands. Figure 5.14 shows that the average of the four on-stage positions is indicative of the stage as a whole (when averaging over 250–2000 Hz octaves).

The TH_{20-50} results that correspond to the TS_{20-50} results in Figures 5.13 and Figure 5.14 are given in Figures 5.15 and Figure 5.16 respectively. Again in Figure 5.16 the average of the four on-stage positions is indicative of the stage as a whole (when averaging over 250–2000 Hz octaves).



(a) Source position S1

(b) Source position S2

(c) Source position S3

(d) Source position S4

Figure 5.13: TS_{20-50} (dB) for each auditorium for 250–2000 Hz octave bands at each source positions on stage.

The spatial parameters presented in this section are discussed further in comparison to the subjective musicians' subjective responses in Section 6.2.2. Tabulated values for TS_{20-50} and

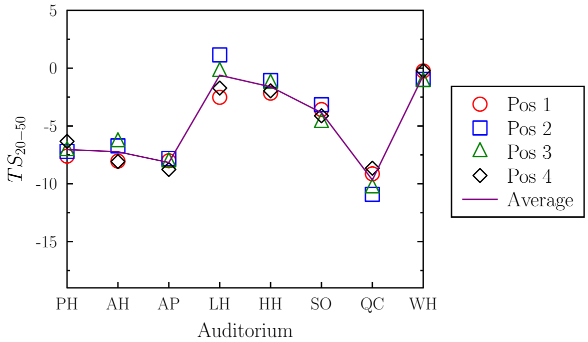
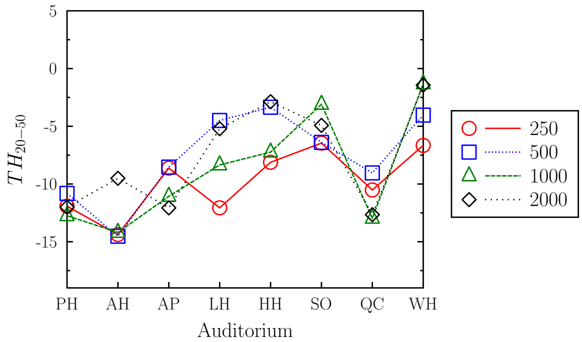
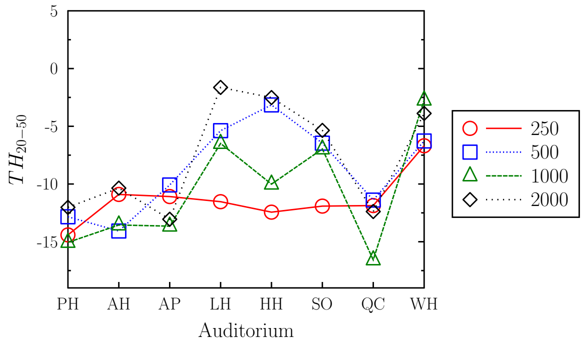


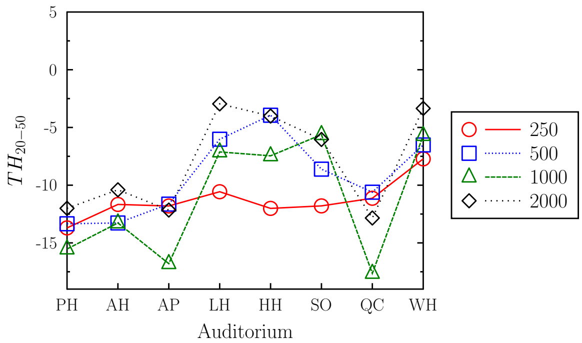
Figure 5.14: TS_{20-50} (dB) power averaged over 250–2000 Hz for positions S1–S4 (shown as markers), and spatially powered averaged to give a stage average over 250–2000 Hz octaves (shown as a solid line).



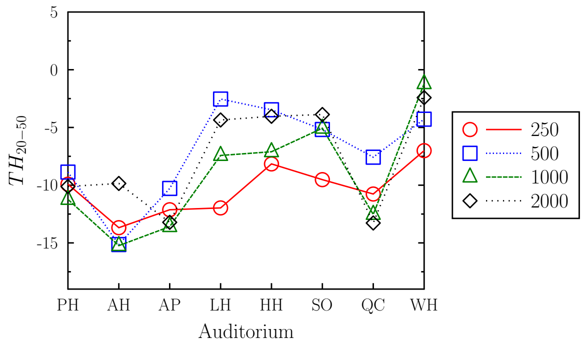
(a) Source position S1



(b) Source position S2



(c) Source position S3



(d) Source position S4

Figure 5.15: TH_{20-50} (dB) for each auditorium for 250–2000 Hz octave bands at each source positions on stage.

TH_{20-50} at the four on-stage source positions and octaves bands 250–2000 Hz are provided in Appendix J.1.2.

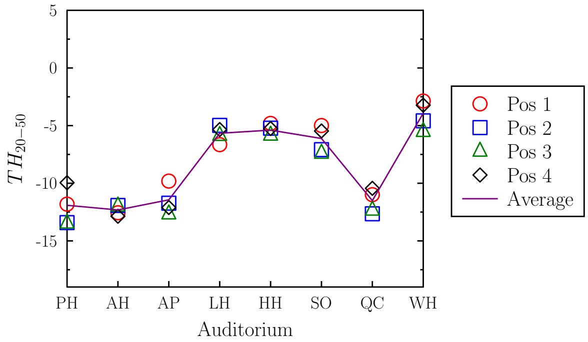
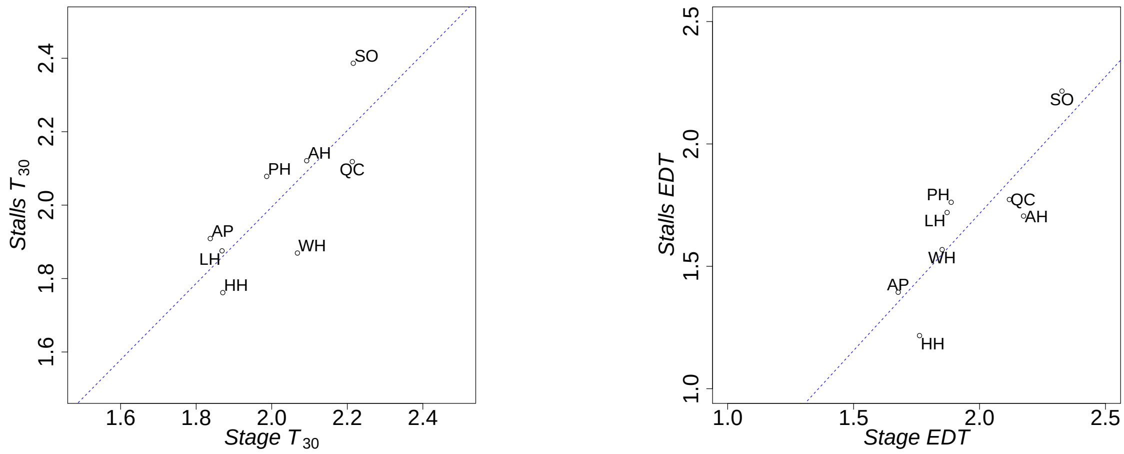


Figure 5.16: TH_{20-50} (dB) power averaged over 250–2000 Hz for positions S1–S4 (shown as markers), and spatially powered averaged to give a stage average over 250–2000 Hz octaves (shown as a solid line).

5.3.4 Stalls measurements

In each auditorium stalls measurements were conducted with the source (Brüel&Kjær omnidirectional loudspeaker type 4295) on stage located 3 m from the front of stage in the centre, and with the receiver in at least six different seats spread throughout the stalls. In PH, AH, AP, HH and QC the receiver used was the Eigenmike. In LH, SO and WH the receiver used was Brüel&Kjær omnidirectional receiver type 4190. A comparison of the common on-stage omnidirectional parameters with the Eigenmike and the Brüel&Kjær omnidirectional receiver (type 4190) is presented in Appendix I. In LH and WH stalls measurements were also taken with the Eigenmike for comparison, and for T_{30} and EDT differences were small (< 0.09 s). The reverberance parameters (T_{30} and EDT) are presented in Table 5.7 for 500–1000 Hz octave band average. A comparison of 500-1000 Hz average in the stalls and on stage is presented in Figure 5.17. The on-stage values of T_{30} and EDT are highly correlated with the values in the stalls ($r = 0.79$ and 0.92 for T_{30} and EDT respectively). Based on this finding it appears when stage measurements of T_{30} or EDT are not available then auditorium stalls measurements of T_{30} or EDT could be correlated with subjective musicians' assessments instead. This has been done in past studies with reasonable success, for example Sanders [2003] found that auditorium average reverberation time correlated with musicians' ratings of subjective reverberance on stage.

Another common auditorium measure is C_{80}, however on-stage values of C_{80} (CS) have shown high correlations with T_{30} [Dammerud, 2009]. Gade [1992] specified ST_{late} should be measured on stage in place of C_{80} (CS) measure impression of reverberance. For these



(a) T_{30} (s), r =0.79, $p = 0.02$ (b) EDT (s), r =0.92, $p < 0.01$

Figure 5.17: Comparison of reverberance parameters on stage and in stalls

reasons C_{80} on-stage was not investigated, and because this work has the primary focus of investigating auditoria for musicians on-stage C_{80} values in the stalls have also not been presented.

Table 5.7: Stalls measurements with source 3 m from front of stage in the centre and receiver located in the stalls (average of at least six source-receiver pairs) for 500–1000 Hz octave band average for T_{30} and EDT.

Parameter	PH	AH	AP	LH	HH	SO	QC	WH
T_{30}	2.08	2.12	1.91	1.88	2.39	2.39	2.12	1.87
EDT	1.89	2.17	1.68	1.87	1.76	2.33	2.11	1.85

5.3.5 Different configurations in ACO auditoria

In Sydney Opera House (SO) the acoustic cloud reflectors were at chamber setting for the previously discussed measurements (see Section 5.3), however measurements were also completed on stage with the cloud reflectors at the maximum height. The change in stage measurements between each configuration is discussed in Section 5.3.5.1. Additionally, in Sydney City Recital Centre, Angel Place (AP) measurements were taken with and without the 2 m stage extension and these results are discussed in Section 5.3.5.2.

5.3.5.1 Sydney Opera House: two configurations

Two acoustic settings were measured in Sydney Opera House: acoustic cloud reflectors at chamber height (approximately 9 m above stage) and acoustic cloud reflectors at maximum height (approximately 22 m above stage). The acoustic cloud reflectors in the chamber setting are shown in Figure 5.18. Subjective testing of musicians' preference in terms of the position of acoustic cloud reflector was not conducted in this study; however, the ACO have a personalised setting in Sydney Opera House, based on the experience of the musicians in the auditoria. This was the setting used during their tour and tested on stage (referred to as the chamber setting). It could be inferred that the highest setting is likely to produce a lower OAI than the one recorded in this study.

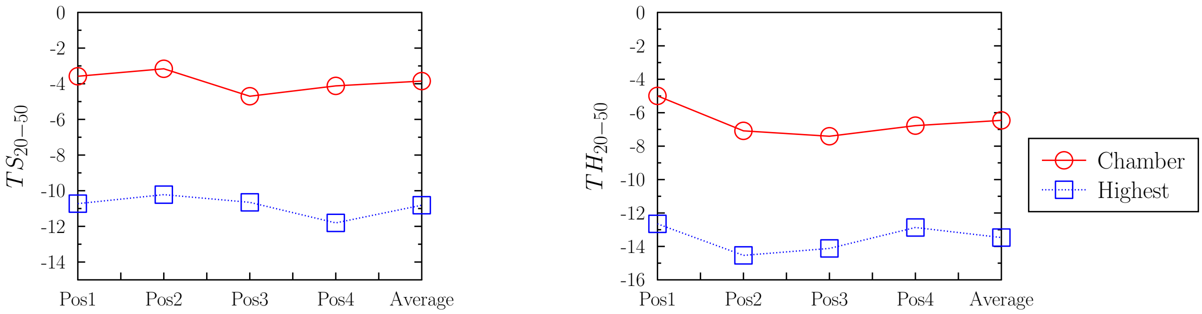
Figure 5.18: The acoustic cloud reflectors in chamber setting position on stage in Sydney Opera House

In Table 5.8 the standard omnidirectional parameters are provided for the two settings investigated. ST_{early} and ST_{late} are the average for all 1 m source-receiver pairs and also averaged over 250–2000 Hz. ST_{early} is increased with the acoustic cloud reflectors lowered (to chamber setting), however by less than 1 dB. ST_{late} decreased with the acoustic cloud reflectors at chamber setting by around 0.5 dB. The changes are less than 2 dB, which is estimated by Gade to be the JND for the support measures. The total area of the cloud reflectors appears to be small in comparison to the total stage area, which explains the small change in support measures with the reflectors in place.

The proposed spatial parameters TS_{20-50} and TH_{20-50} were also investigated on stage in SO for the two settings. In Figure 5.19a, the 250–2000 Hz average for TS_{20-50} is shown for the

Table 5.8: Omnidirectional parameters for SO with cloud reflectors at chamber setting and at the highest setting

Parameter	SR dist. (m)	Chamber setting	Highest setting
ST_{early} (250-2000 Hz)	1	-14.3	-15.1
ST_{late} (250-2000 Hz)	1	-15.2	-14.7



(a) TS_{20-50} (b) TH_{20-50}

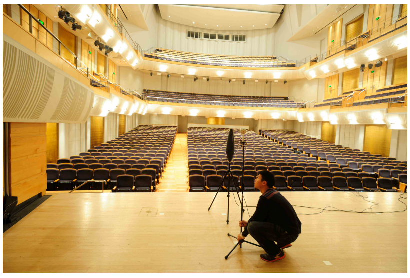
Figure 5.19: Average TS_{20-50} and TH_{20-50} (found with 2$^{\text{rd}}$-order Ambisonics) for 1 m source-receiver pairs at each source position, power averaged over 250–2000 Hz for SO with acoustic cloud reflectors at chamber setting and at highest setting. Average is also included which is the power average for all 1 m source-receiver pairs and 250–2000 Hz octave bands.

four source positions (as well as a power average), and TS_{20-50} is notably increased when the acoustic cloud reflectors are in place, indicating more sound energy from 'above' relative to the 'sides'. This is intuitive as the reflectors will provide more early reflections from 'above', and the amount of reflections from the 'sides' will be unchanged. A similar change is observed for the parameter TH_{20-50} (Figure 5.19b). The fact that such large changes in TS_{20-50} and TH_{20-50} are produced by a relatively small area suggests that the low TS_{20-50} and TH_{20-50} values for the highest setting predominantly indicate a lack of 'top' energy in the interval 20–50 ms, as opposed to presence of any significant 'sides' energy. This is unsurprising given the 22 m height above stage. In Section 6.2.1 (Chapter 6), the implications of the results presented here are discussed further in relation to the general findings regarding musicians' preferences.

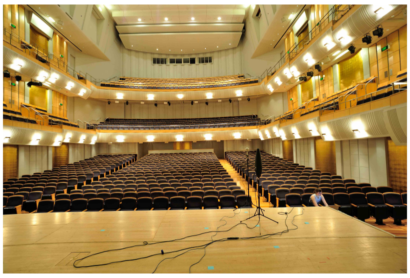
5.3.5.2 Angel Place: two configurations

In AP stage measurements were conducted with and without the 2 m stage extension, see Figure 5.20. This was done because the stage configuration for the ACO was not known when the initial acoustic measurements were made. The 2 m stage extension was used by ACO and these results have been presented previously. Note in each case the measurement positions on stage were relative to the front of stage, see Figure 5.7. This means in the case of the 2 m stage extension the measurement locations would have been shifted away from the back of the stage (i.e. shifted downstage). A comparison of omnidirectional parameters with and without the extension is provided in Table 5.9. The ST measures are arithmetically averaged over 250–2000 Hz for all 1 m source-receiver pairs. The variations on sound strength (G_{7-50}, G_e and G_l) are power average for all 2.7 m source-receiver distances at 1 kHz octave band. Minimal differences were noted for both support measures (<0.2 dB) and the variations of sound strength (<0.4 dB). The spatial parameters (TS_{20-50} and TH_{20-50}) were also compared with and without the stage extension (Figure 5.21), and the differences were generally within 1 dB.

Although these results are not surprising, since the stage extension was small, it is validation that measurements taken on-stage with/without a small stage extension (<2 m) in place do not differ. In particular, recall from Section 5.3.1 that in the case of AH a 3.7 m stage extension was used during measurements whereas ACO played with a 4.9 m stage extension in place (additional 1.2 m relative to the stage measurement configuration). The AP results therefore provide confidence that the measurements in AH can be used in the subjective and objective comparisons.



(a) AP without stage extension

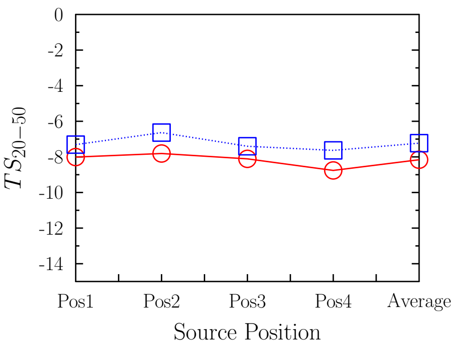


(b) AP with 2 m stage extension in place

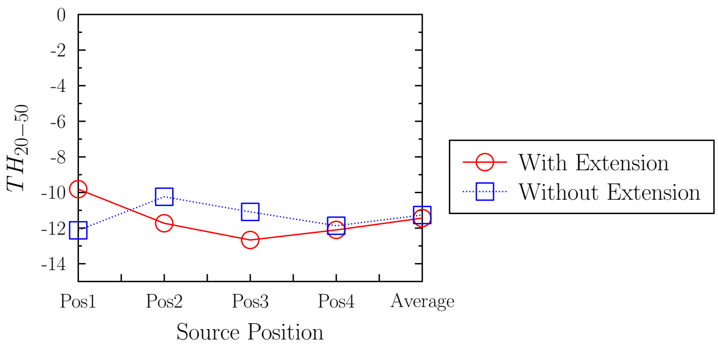
Figure 5.20: AP with and without stage extension

Table 5.9: Omnidirectional parameters for AP with and without 2 m stage extension

Parameter	SR dist. (m)	With Extension	Without Extension
ST_{early} (250-2000 Hz)	1	−11.8	−11.6
ST_{late} (250-2000 Hz)	1	−13.5	−13.5
G_{7-50} (500-2000 Hz)	2.7	8.1	8.0
G_e (500-2000 Hz)	2.7	13.9	14.0
G_l (500-2000 Hz)	2.7	7.2	6.9



(a) TS_{20-50}



(b) TH_{20-50}

Figure 5.21: Average TS_{20-50} and TH_{20-50} (found with 2$^{\text{rd}}$-order Ambisonics) for 1 m source-receiver pairs at each source position, power averaged over 250–2000 Hz for AP with and without 2 m stage extension. Average is also included which is the power average for all 1 m source-receiver pairs and 250–2000 Hz octave bands.

5.4 Auditoria assessed by chamber ensembles

The auditoria assessed by at least one chamber ensemble are listed in Table 5.10 in comparison to those assessed by ACO and ACO2 (for more information on auditoria assessed by chamber ensembles see Appendix B). The stage measurements in PH, AH, AP and LH were presented as part of the ACO dataset, and the stage measurements in ARM are discussed later as part of the ACO2 dataset. In this section the stage measurements for the remaining two halls measured (MC and HT) are detailed. The auditorium and stage dimensions (as well as architectural measures) for these two halls are provided in Table 5.11. Measurements were not conducted in QT, HL or CH.

Acoustics measurements were conducted in Elisabeth Murdoch Concert Hall, Melbourne Recital Centre (MC) on stage and in the stalls. Source-receiver height used on stage was 1.5 m to allow direct comparison to measurements conducted in auditoria visited by ACO.

Table 5.10: Auditoria assessed by chamber ensembles, in comparison to those assessed by chamber orchestras. The ∘ symbol indicates the hall was assessed by this group, the × symbol indicates the hall was assessed by this group *and* has been acoustically measured as part of this study.

	Chamber Ensemble 1	Chamber Ensemble 2	Chamber Ensemble 3	ACO	ACO2
AP	×	×		×	
AH	×	×	×	×	
QT	∘	∘			
MC	×		×		
HT	×	×			
LH	×		×	×	
HL	∘	∘			
ARM		∘			×
CH		∘			

The source positions used were the same as for ACO auditoria measurements (Figure 5.7), and 1 m measurements were conducted in four positions around each source position (S1–S4) as well as the 12 across-stage measurements. Results for omnidirectional parameters for MC are summarised in Table 5.12, where T_{30} and EDT arithmetically averaged for all across-stage measurements and for 500-1000 Hz octave bands, and ST_{early} and ST_{late} are arithmetically averaged for all 1 m measurements and for 250–2000 Hz, and G_{7-50}, G_e and G_l are power averaged for 2.7 m source-receiver distances and over 500–2000 Hz octave bands, and the measurements in the stalls are an average of six measurements.

Acoustic measurements were conducted in the Hobart Town Hall (Figure 5.22a) on stage and in the audience area. Source-receiver height used on stage was 1.5 m. Due to the small stage size the source-receiver locations were adapted. Using the same coordinate system as Figure 5.7 the coordinates of S1 were (−1.5,−1), S2 were (−0.75,−2), S3 were (0.75,−2) and S4 were (1.5,−1). Support measurements were taken at four positions around S2 and S3 with 1 m source-receiver distance (in positions front, back, left and right). Across-stage measurements were undertaken with source at S1 and receiver at all other positions, and with source at S2 and receiver at all other positions. Results for omnidirectional parameters for HT are summarised in Table 5.13. Note, for HT the modified G parameters (G_{7-50}, G_e and G_l) are not presented, because the source-receiver distances used in this auditoria were smaller than in the other auditoria in the ACO dataset and in MC. The values of modified G parameters depend on the source-receiver distance, and so presenting these parameters in HT would not be comparable to the other across-stage measurements. The across-stage measurements in HT were used to calculate a stage T_{30} and EDT value. Recall the stage in HT was too small to use the same source-receiver pairs as used in the other auditoria.

The spatially-defined acoustic stage parameters (TS_{20-50} and TH_{20-50}) are provided in Table 5.14 for MC and HT. These are the power average over 250–2000 Hz octaves, and for all 1 m on stage measurements. Results for individual source positions and octaves bands 250–2000 Hz are provided in Appendix J.1.2. There results are discussed further in comparison to subjective musician preferences in Appendix C.

Table 5.11: Auditorium and stage dimensions and architectural measures for auditoria visited by chamber ensembles only, where W is width to side reflecting surfaces, H is the height from stage to above reflecting surfaces and D is the stage depth.

	Room volume (m^3)[a]	Stage area (m^2)[a]	Stage width front (m)	Height above stage (m)	Stage depth (m)	W (m)	H (m)	D (m)	H/W	$H/\sqrt{D \cdot W}$
MC	9800	135	17	9.5	9	18.2	9.5	9	0.52	0.74
HT	200	33	9.8	7.5	3.4	9.8	7.5	3.4	0.77	1.30

[a] Room volumes and stage areas have generally been estimated from auditorium dimensions (approximate only)

(a) HT

(b) MC

Figure 5.22: Auditoria assessed by chamber ensembles

Table 5.12: Omnidirectional parameters for MC

	Parameter	MC
Stage	ST_{early} (250-2000 Hz)	-10.5
	ST_{late} (250-2000 Hz)	-12.5
	G_{7-50} (500-2000 Hz)	5.8
	G_e (500-2000 Hz)	12.7
	G_l (500-2000 Hz)	7.9
	T_{30} (500-1000 Hz)	2.2
	EDT (500-1000 Hz)	1.9
Stalls	T_{30} (500-1000 Hz)	2.2
	EDT (500-1000 Hz)	2.2

Table 5.13: Omnidirectional stage parameters for HT

	Parameter	HT
Stage	ST_{early} (250-2000 Hz)	-8.1
	ST_{late} (250-2000 Hz)	-12.2
	T_{30} (500-1000 Hz)	2.1
	EDT (500-1000 Hz)	1.7
Stalls	T_{30} (500-1000 Hz)	2.0
	EDT (500-1000 Hz)	2.0

Table 5.14: Spatial parameters for MC and HT

Parameter	MC	HT
TS_{20-50} (250-2000 Hz)	-5.3	-3.2
TH_{20-50} (250-2000 Hz)	-10.5	-7.1

5.5 Auditoria assessed by ACO2

Acoustic measurements were also conducted in five multi-purpose halls, which ACO2 played in during a tour in May 2015. The five multi-purpose halls measured are given in Table 5.15. In the following sections the auditoria are given in order of preference, as rated by ACO2, where BEL was the highest-rated hall and BUN was the lowest-rated hall.

Table 5.15: Measured auditoria assessed by ACO2

Auditorium	Location	Auditorium Identifier
Bellingen Memorial Hall	Bellingen, NSW	BEL
Auditorium at Redland Performing Arts Centre	Cleveland, Qld	CLE
St John's School Hall	Mullumbimby, NSW	MUL
Armidale Town Hall	Armidale, NSW	ARM
Moncrieff Theatre	Bundaberg, Qld	BUN

From Section 3.4 there are three auditoria from the ACO2 tour which were not measured; these are Gladstone Entertainment Centre (GLA), Gold Coast Arts Centre (GOL) and Nambour Civic Centre (NAM). GLA and GOL were both conference rooms with tables and chairs, rather than a traditional concert space with permanent seating. Acoustic measurements have not been conducted in these spaces since the configuration in the space is highly adjustable, and they cannot be considered normal spaces for chamber music and it was unusual for the ACO2 to play in these spaces. NAM was the least preferred hall on the ACO2 tour, however this space closed shortly after the ACO2 performed there. Therefore, five of the total of eight auditoria on the ACO2 tour have been measured. The stages measured are shown in Figure 5.23 and the stage and auditoria dimensions (as well as architectural measures) are provided in Table 5.16. Stage diagrams are also included in Appendix H for ACO2 auditoria measured. In ARM there is a proscenium arch and a height to reflecting surfaces above (H) and a width to side reflecting surfaces (W) have not been defined since these measures are highly dependent on location on stage.

5.5.1 Measurement procedure in ACO2 auditoria

Figure 5.24 shows the on-stage measurement locations used in the ACO2 halls. The source locations were altered from those used in the purpose-built auditoria due to the smaller stage sizes. In BEL, the orchestra played on a makeshift stage in the auditoria (due to poor lighting on-stage), and measurements were conducted with this same setup. Additionally, in ARM the source positions were shifted by 0.2 m in the negative x direction due to the unusual stage shape, and in MUL, the back source positions (S3 and S4) were shifted forward to 3 from front of stage (due to small stage size). In the multi-purpose hall measurements with the source on stage (2 m from front of stage on the centreline) and receiver within the

Table 5.16: Auditorium and stage dimensions and architectural measures for auditoria visited by ACO2, where W is width to side reflecting surfaces, H is the height from stage to above reflecting surfaces and D is the stage depth.

	Room volume (m^3)[a]	Stage area (m^2)[a]	Stage width front (m)	Height above stage (m)	Stage depth (m)	W	H	D	H/W	$H/\sqrt{D \cdot W}$
BEL[b]	3290	35	7.2	7.8	4.9	14.4	7.8	4.9	0.55	0.94
CLE	1390	43	7.7	3.8	5.6	7.7	3.8	5.6	0.48	0.58
MUL	1870	37	8.4	7.7	4.3	8.4	7.7	4.3	0.92	1.28
ARM	3140	74	8.8	4.6–8	9	8.8	N/A	N/A	N/A	N/A
BUN	3420	131	16.7	9.6	11	16.7	9.6	11	0.57	0.71

[a] Room volumes and stage areas have generally been estimated from auditorium dimensions (approximate only)
[b] Stage dimensions refer to the makeshift stage used by ACO2

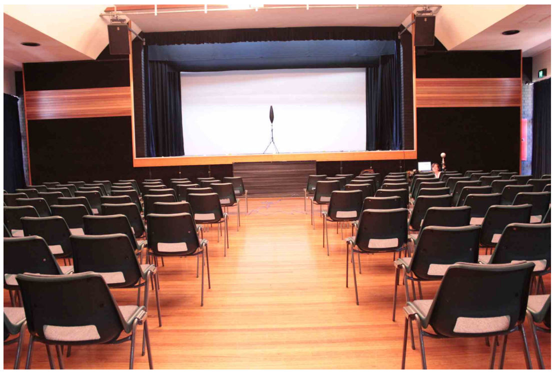
stalls area were also conducted.

The same source and receiver were used for measurements in these auditoria as for those previously presented: Brüel&Kjær omnidirectional loudspeaker type 4295 and Eigenmike 32 respectively. However, in three auditoria (CLE, MUL and BUN) unfortunately only 16 of the 32 channels on the Eigenmike spherical microphone array were operating due to hardware/software setup errors. This affected the spherical microphone characteristics, and this is discussed in Section 5.5.2. Note, that in BEL and ARM the microphone was operating normally. The spherical microphone array characteristics in CLE, MUL and BUN are discussed in Section 5.5.2.

5.5.2 Spherical microphone characteristics

As discussed in Section 5.5.1 only 16 of 32 capsules were operational for measurements in CLE, MUL and BUN. To assess the spherical microphone array characteristics of the Eigenmike with these 16 capsules functioning, the directivity index (DI) and standard deviation of the directivity for each frequency were recalculated for this configuration, using the same methods described previously in Section 5.2.4. The resulting DI curves and standard deviations are shown in Figures 5.25a and 5.25b respectively, and show the range of frequencies where the array performs best at a maximum and constant directivity for all directions.

(a) BEL



(b) CLE

(c) MUL

(d) ARM

(e) BUN

Figure 5.23: Images of two of the auditoria visited by ACO2 during May 2015 tour

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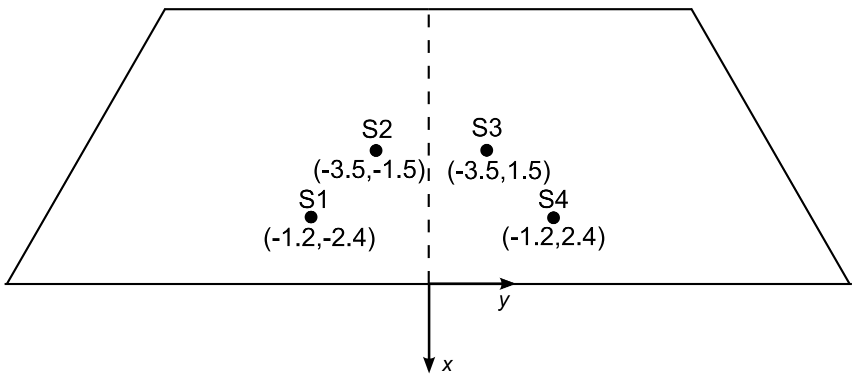
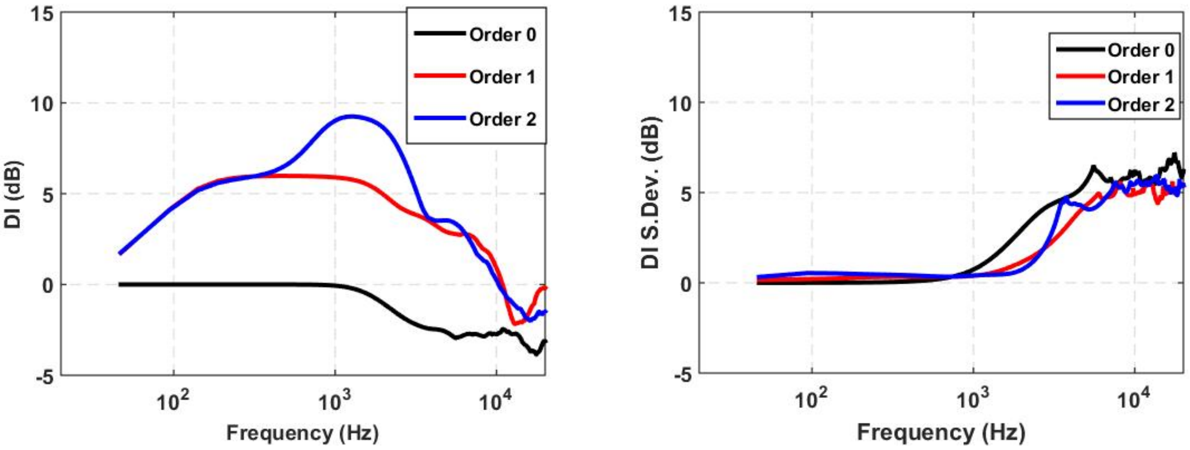


Figure 5.24: The on-stage measurement locations for ACO2 regional halls. Dimensions in metres. The coordinate system is located at the center front of the stage. Receivers had the same locations for across-stage measurements, and were at positions (1,0), (0,1),(-1,0) and (0,-1) relative to the sources for the 1 m measurements.

The standard deviation curves show that for the microphone working with only 16 capsules, the direction of the beam and of the impinging wave have a greater influence in the result than the DI curves for the microphone with 32 capsules (shown previously in Figure 5.4a). However, these plots also show that at lower frequencies (up to 1 kHz), the direction of the impinging waves for the omnidirectional processing has close to no influence on the results and the microphone behaves in an omnidirectional manner. Because of these compromised results in three auditoria (CLE, MUL and BUN) omnidirectional parameters will be presented for 250, 500 and 1000 Hz octave bands only (and the 2000 Hz octave band will be excluded) for the halls in the ACO2 dataset, and spatial analysis of on-stage sound fields will not be explored for this dataset.

5.5.3 Omnidirectional stage parameters

The ST parameters are presented in Table 5.17 for average of 250–1000 Hz octave bands (arithmetic). ST_{early} and ST_{late} are also presented at individual octaves and source positions in Figures 5.26 and 5.27 respectively. The ST parameters are usually averaged over 250–2000 Hz octaves, however as discussed in Section 5.5.2 the 2000 Hz octave is excluded due to the microphone directivity in this octave (for CLE, MUL and BUN). In Table 5.17 the 250–2000 Hz octave band average are included for BEL and ARM; the difference between 250–1000 Hz average and 250–2000 Hz average is within 0.2 dB for these halls. For the ACO dataset the 2000 Hz octave agreed well with 250–1000 Hz octaves as well (see Figures 5.8 and 5.9).



(a) Directivity index (DI) versus frequency for the Eigenmike, varying with HOA order N.

(b) Directivity index (DI) standard deviations (S. Dev.) for directivity versus frequency for the Eigenmike, varying with HOA order N.

Figure 5.25: Microphone characteristics for Eigenmike with 16 capsules. The code used to produce these figures has been implemented in AARAE by Luis Miranda.

In some cases, ST_{early} has been adjusted because the stages were considerably smaller than those in the purpose built auditoria used by ACO. Recall from Section 2.3, the lower integration time of 20 ms for ST_{early} should be reduced on smaller stages. For example, Chiang et al. [2003] used $ED100$, which is a modified version of ST_{early} where the integration time of 20–100 ms is altered to 7-100 ms. The 1 m impulse response measurements were assessed individually to select an appropriate choice for the lower integration time in each case. Note, if no reflections occur between the direct sound/floor reflection and 20 ms then the choice of the lower integration time should be completely arbitrary; however, on smaller stages the lower integration time should be reduced to capture reflections arriving before 20 ms. The halls in this dataset had small stage enclosures, see Table 5.16 and it was difficult to accurately isolate direct sound and floor reflections from early arriving reflections (particularly with the source-receiver at 1.5 m from stage floor). This effects the reliability of the ST_{early} parameter (where either the direct sound and floor reflection is not fully truncated or early reflections are omitted), whereas for the ST_{late} parameter late reflections can be easily separated from the direct sound and floor reflection.

The results for on stage T_{30} are presented in Table 5.18, and for EDT in Table 5.19. The reverberance parameters are averaged for all across-stage source-receiver pairs (source-receiver distances between 2.5 and 4.8 m).

The omnidirectional parameters presented in this section are discussed further in comparison to the subjective musicians' response in Section 6.3. The support parameters for these auditoria over individual source positions and octaves 250–1000 Hz are provided in Appendix J.2.

Table 5.17: ST parameters arithmetically averaged over all 1 m source-receiver measurements and over 250–1000 Hz octave bands in all halls (and over 250–2000 Hz in BEL and ARM).

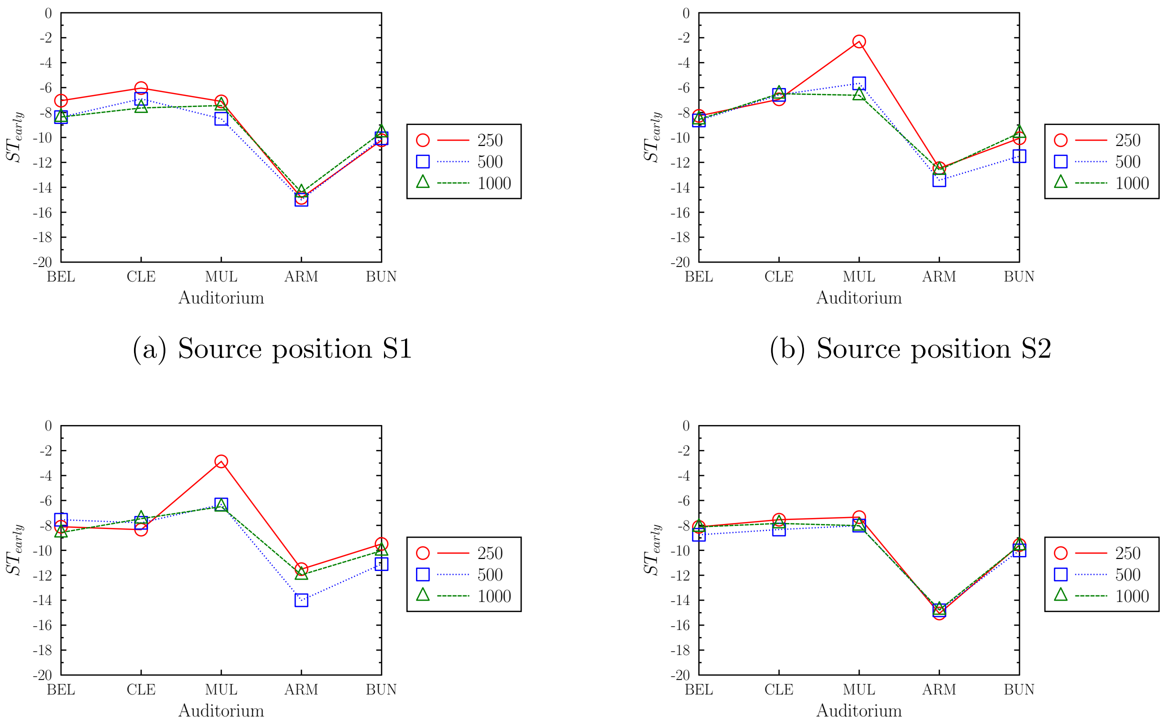
Parameter	SR dist. (m)	BEL	CLE	MUL	ARM	BUN
ST_{early} (250-1000 Hz)	1	-8.2	-7.3	-6.4	-13.7	-10.1
ST_{late} (250-1000 Hz)	1	-11.4	-11.9	-12.1	-14.4	-16.7
ST_{early} (250-2000 Hz)	1	-8.3	-7.4	-	-	-
ST_{late} (250-2000 Hz)	1	-11.6	-12.0	-	-	-

Table 5.18: T_{30} (seconds) on stage: average for all across-stage source-receiver pairs for individual octave bands 250–1000 Hz

Octave (Hz)	SR dist. (m)	BEL	CLE	MUL	ARM	BUN
250	> 2.5	1.28	1.22	1.10	1.46	1.01
500	> 2.5	1.32	1.12	1.11	1.19	0.90
1000	> 2.5	1.31	1.21	1.24	1.00	1.01

Table 5.19: EDT (seconds) on stage: average for all across-stage source-receiver pairs for individual octave bands 250–1000 Hz

Octave (Hz)	SR dist. (m)	BEL	CLE	MUL	ARM	BUN
250	> 2.5	1.10	1.06	1.01	1.11	0.57
500	> 2.5	1.29	1.02	0.78	1.27	0.69
1000	> 2.5	1.22	0.94	0.68	0.96	0.56



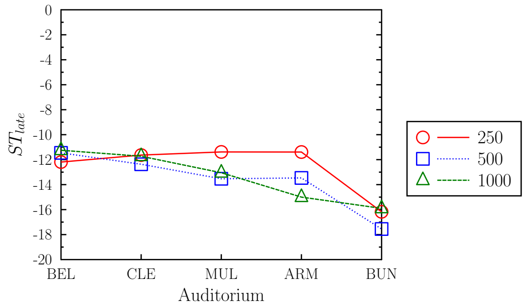
(a) Source position S1

(b) Source position S2

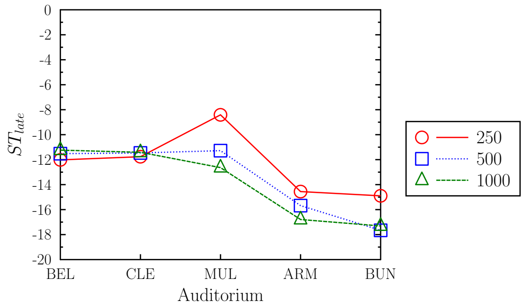
(c) Source position S3

(d) Source position S4

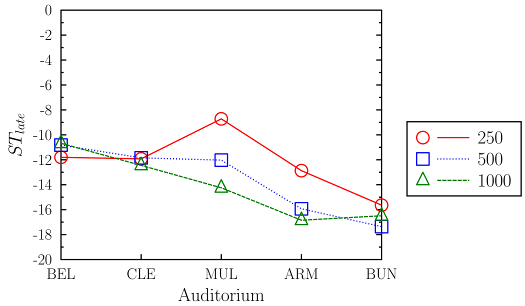
Figure 5.26: ST_{early} (dB) compared to auditorium for 250–1000 Hz octave bands at source positions on stage for ACO2 auditoria.



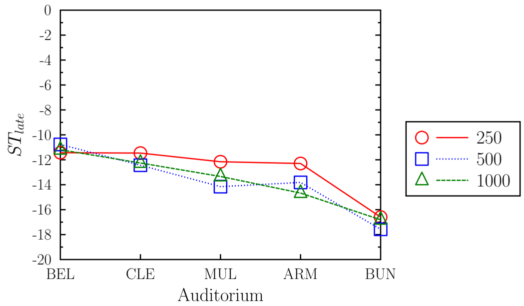
(a) Source position S1



(b) Source position S2



(c) Source position S3



(d) Source position S4

Figure 5.27: ST_{late} (dB) compared to auditorium for 250–1000 Hz octave bands at source positions on stage for ACO2 auditoria.

5.6 Correlations between acoustic parameters and architectural measures

In this section correlations are considered between acoustic stage parameters and architectural measures (such as stage dimensions or ratios of stage dimensions). The purpose here is to consider whether information derived from acoustic measurements on stage can actually be inferred from simple architectural parameters. Firstly, omnidirectional parameters and stage dimensions are considered and then the spatially-defined parameters are examined in relation to stage dimension ratios. The halls in the ACO dataset have been presented separately, as well as the ACO halls combined with all other halls measured. This was done to demonstrate whether simple architectural measures would have been as valid in these purpose-built concert halls (assessed subjectively by ACO) or whether the acoustic parameters considered provide different information.

5.6.1 Omnidirectional parameters

Linear correlation coefficients (r_l) have been investigated between omnidirectional stage parameters and architectural measures. Past studies have found a relationship between support measures and stage volume [Gade, 1989a, Hidaka and Nishihara, 2004]. A stage volume can be difficult to define depending on the design of the stage enclosure. In some halls there wasn't a stage enclosure and the front of the auditoria provided reflections to the musicians. Instead of stage volume, distances to reflecting surfaces (W, H and D) have been considered in comparison the ST measures. Recall, W is width to side reflecting surfaces, H is the height from stage to above reflecting surfaces and D is the stage depth.

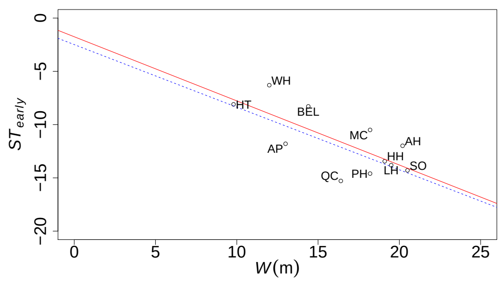
In Figure 5.28 regression analysis has been used to compare ST parameters (ST_{early} and ST_{late}) to the H, D and W measures for two cases: (1) the ACO dataset ($N = 8$) and (2) the ACO dataset combined with four additional halls (MC, HT, ARM and BEL) ($N = 12$). However, in some cases ARM was excluded because the architectural measures could not be defined for this hall, see Table 5.16, and the sample size was then $N = 11$.

ST_{early} was found to correlate well with all the architectural measures: W ($r_l = -0.73$, $p = 0.01$, $N = 11$), H ($r_l = -0.76$, $p < 0.01$, $N = 11$) and D ($r_l = -0.76$, $p < 0.01$, $N = 12$).

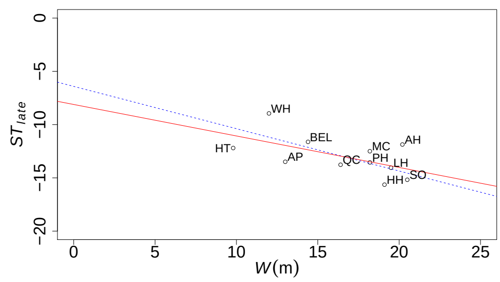
When the stage is smaller there are stronger early reflections increasing ST_{early}, as indicated by the negative linear correlation coefficients (r_l). ST_{late} did not correlate as closely with W, H and D, although the in general the trends indicate higher ST_{late} values on smaller stages. ST_{late} assesses late arriving sound energy and a strong correlation between the distances to stage enclosure (causing early reflections) and ST_{late} is not necessarily expected. The relationship between stage dimensions and ST_{late} may be because small stages are usually found in small halls.

5.6.2 Spatial parameters

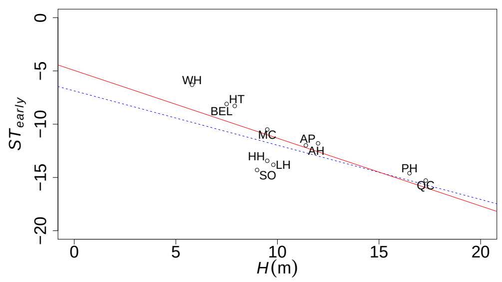
Linear correlation coefficients (r_l) have been investigated between spatial acoustic measures and architectural measures. The architectural measures investigated here are combinations of W, H and D (recall, W is width to side reflecting surfaces, H is the height from stage to above reflecting surfaces and D is the stage depth). In Figure 5.29 regression analysis has been used to compare the spatially-defined stage parameters (TS_{20-50} and TH_{20-50}) to appropriate architectural measures for two cases: (1) the ACO dataset ($N = 8$) and (2) the ACO dataset combined with three additional halls (MC, HT and BEL) ($N = 11$). ARM was excluded because the architectural measures could not be defined for this hall, see Table 5.16. The two architectural measures consider here are: H/W and $H/\sqrt{D \cdot W}$. H/W is simply a ratio of height to reflecting surfaces on stage and width to reflecting surfaces on stage, and will be related to TS_{20-50}. $H/\sqrt{D \cdot W}$ is a ratio of height to reflecting surfaces of stage and stage depth times width to reflecting surfaces, with the square root taken for the the denominator of the ratio (the square root is used to give a dimensionless quantity), and will be related TH_{20-50}. In Figure 5.29a TS_{20-50} has been compared to H/W and the relationship is significant for the ACO dataset and for the dataset including the three extra halls. In Figure 5.29b TH_{20-50} has been compared $H/\sqrt{D \cdot W}$ and the relationship is significant for the ACO dataset, whereas with the extra three halls included the relationship is no longer significant. Overall, it is clear that when spatial parameters cannot be measured (i.e. when a spherical microphone array is not available) it is well-worth considering the ratios simple architectural measures to assess the directionality of on stage sound fields. However, note that the halls in this study quite commonly had a shoe-box stage enclosure making simple architectural measures quite valid, whereas for a more complex stage enclosure geometry the spatial parameters measured with a spherical microphone array are unlikely to be fully characterised with architectural measures.



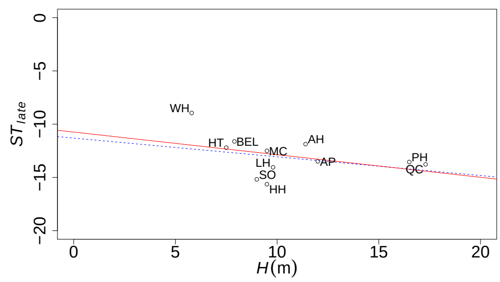
(a) ST_{early} (250–2000 Hz) vs. W
ACO: $r_l = -0.67$, $p = 0.07$
All(ARM excluded): $r_l = -0.73$, $p = 0.01$



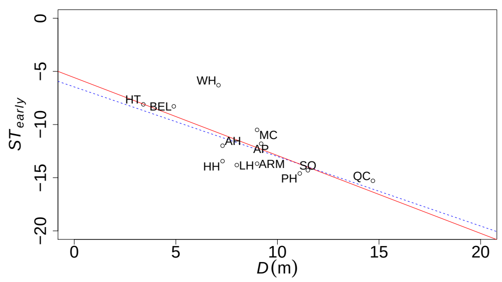
(b) ST_{late} (250–2000 Hz) vs. W
ACO: $r_l = -0.62$, $p = 0.10$
All(ARM excluded): $r_l = -0.58$, $p = 0.06$



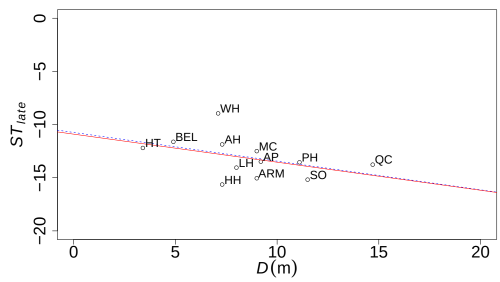
(c) ST_{early} (250–2000 Hz) vs. H
ACO: $r_l = -0.69$, $p = 0.06$
All (ARM excluded): $r_l = -0.76$, $p < 0.01$



(d) ST_{late} (250–2000 Hz) vs. H
ACO: $r_l = -0.10$, $p > 0.05$
All(ARM excluded): $r_l = -0.41$, $p > 0.05$

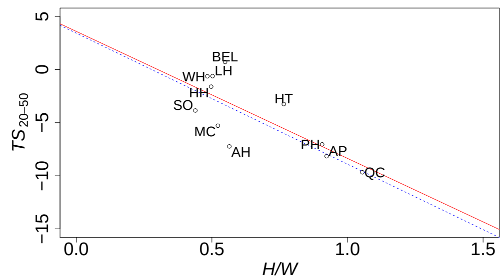


(e) ST_{early} (250–2000 Hz) vs. D
ACO: $r_l = -0.62$, $p = 0.10$
All: $r_l = -0.75$, $p < 0.01$

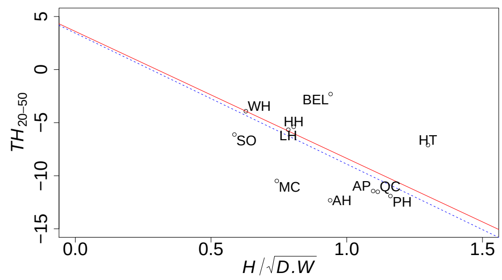


(f) ST_{late} (250–2000 Hz) vs. D
ACO: $r_l = -0.35$, $p > 0.05$
All: $r_l = -0.42$, $p > 0.05$

Figure 5.28: Relationships between ST parameters and architectural measures. Linear regression lines are shown for ACO halls only (blue dashed) and for ACO halls combined with other halls (red solid).



(a) TS_{20-50} (250–2000 Hz) vs. H/W
ACO: $r_l = 0.84$, $p < 0.01$
All (ARM excluded): $r_l = -0.74$, $p < 0.01$



(b) TH_{20-50} (250–2000 Hz) vs. $H/\sqrt{D \cdot W}$,
ACO: $r_l = -0.88$, $p < 0.01$
All (ARM excluded): $r_l = -0.46$, $p > 0.05$

Figure 5.29: Relationships between spatially-defined acoustic parameters and architectural measures.

5.7 Conclusion

In this chapter on-stage measurements and measurements in the stalls have been presented in 15 Australian halls, in some cases for multiple acoustic settings. Traditional omnidirectional stage parameters, as well as spatially defined parameters, have been presented. Consideration was given to variation in stage parameters around the stage, and in general stage averages have been shown to be indicative of the stage as a whole when considering the area on stage in which a chamber orchestra will play and when considering the ST parameters measured with 1 m source-receiver distance. When considering the across-stage measurements, and examining the modified sound strength parameters (G_{7-50}, G_e and G_l), the values depended on source-receiver distance and stage averaging was not used. Two spatially defined parameters were proposed in this chapter: one to assess sound energy on stage from the above relative to sides, and another which adapted this parameter to include sound energy on stage from the 'back' (with the sides). For these parameters, with 1 m source-receiver distance and 250–2000 Hz octave averaging, the stage averages were indicative of the stage as a whole (when examining the area on stage used by a chamber orchestra). It must be noted that the measurements presented in this study were conducted on unoccupied concert hall stages (and audience areas also were unoccupied). Overall, stage measurements without the orchestra present on stage may not capture all information about the acoustic experience on stage for musicians, however these measurements are more repeatable and will still provide considerable information about acoustic conditions on stage. The presence of an audience also alters acoustic parameters, particularly those parameters used to assess reverberance, such as T_{30}. The difference between occupied and unoccupied audience conditions depends on the level of seating upholstery, however in purpose-built concert halls (such as those assessed by ACO) seats are designed to have similar acoustic properties when occupied and unoccupied. In the following chapter the measurements presented here will be compared to musicians' rating.

Chapter 6

Assessing stage acoustics in Australian concert halls: subjective and objective results

6.1 Introduction

In this chapter the objective stage measurements in Australian concert halls are compared to the subjective data collected from musicians regarding their experiences performing on stage in the same auditoria.

The subjective responses from the Australian Chamber Orchestra (ACO) are compared to acoustic measurements in purpose-built concert halls in Section 6.2, focusing on omnidirectional stage parameters, spatially-defined stage parameters and architectural measures. The subjective responses from ACO2 are compared to stage measurements in multi-purpose halls in Section 6.3.

Three chamber ensembles were also surveyed as part of this study (in some cases in halls assessed by ACO and ACO2). Due to the size of the chamber ensembles (between 2–4 players) the sample size in each chamber ensemble dataset is low and the results haven't been included in this chapter. However, for reference the subjective responses from the chamber ensembles are discussed in comparison to the acoustic measurements and other musician assessments of these auditoria in Appendix C.

In this chapter regression analysis is used to compare the subjective and objective datasets. In Chapter 5 omnidirectional and spatially-defined stage parameters were presented for the stages which have been subjectively assessed by musicians, and in most cases stage parameters did not vary around the stage (in the region occupied by a chamber orchestra) and stage average values were indicative of the stage as whole. This was particularly the case for 1 m measurements. Averaging 1 m measurements around the stage is also in line with the procedure used by Gade [1992] for the measurement of the ST parameters. In this chapter unless otherwise noted stage average values have been used to compare to musicians' rating.

Orchestra median values are used in this study to allow a single rating for each stage. As discussed in Chapter 3 the data in this study were collected from musicians while on tour (to control for factors such as repertoire, position on stage, instrument and memory), and this resulted in good general agreement between musicians regarding the acoustics of the auditoria. The use of a median orchestra value rather than a mean orchestra value is discussed further in Section 6.2.

In this chapter regression analysis has been used to compare the subjective ratings and objective measures. In some cases linear regression has been used, and the correlation coefficient has been labelled r_l. The linear correlation coefficients are provided with a sign to indicate the direction of the relationship. In other cases a quadratic regression is used. A quadratic regression was studied if a visual inspection of the data indicated this was warranted, and additionally a quadratic regression can help to indicate a possible optimum range of the parameter. The quadratic correlation coefficients are provided as an absolute value and labelled $|r_q|$. For regression analysis the significance level is also provided as a p value. Significance at the 5% level is used to distinguish between a significant ($p < 0.05$) or non-significant result ($p > 0.05$). In some cases p values above 0.05 are specified to aid in the discussion of results.

6.2 Subjective and objective results: Auditoria assessed by ACO

The subjective data from the Australian Chamber Orchestra (ACO) was obtained during a tour in June 2015 and has been discussed in Chapter 3. The objective data has been collected on stage and in the stalls in the same eight auditoria subjectively assessed by ACO, and these measurements have been discussed in Chapter 5. Recall the auditoria (with the auditorium identifier included in brackets) are Perth Concert Hall (PH), Adelaide Town Hall (AH), Sydney City Recital Hall Angel Place (AP), Llewellyn Hall Canberra (LH), Hamer Hall Melbourne (HH), Sydney Opera House Concert Hall (SO), QPAC Queensland Performing Arts Centre Brisbane (QC) and Wollongong Town Hall (WH).

In this section the objective measurements and subjective musician data are discussed together, first focusing on traditional omnidirectional parameters in Section 6.2.1, second focusing on spatial analysis of on-stage sound fields in Section 6.2.2 and third focusing on simple architectural measures based on stage geometry in Section 6.2.3. When comparing to subjective musicians' ratings the median of the subjective characteristics, such as overall acoustic impression (OAI), have been used. In some cases the musicians did not form a consensus regarding the overall acoustic impression on stage. This was most notably the case in Queensland Performing Arts Centre (QC). As discussed in Section 3.7, QC was polarising and while the majority of musicians rated it well, a small number gave very low scores on OAI (as low as 1/10). Using the mean orchestra rating would give too much weight to the small number of musicians who gave very poor ratings in this auditoria, and hence the median rating was considered for this auditorium, and all others in the dataset.

6.2.1 Omnidirectional parameters

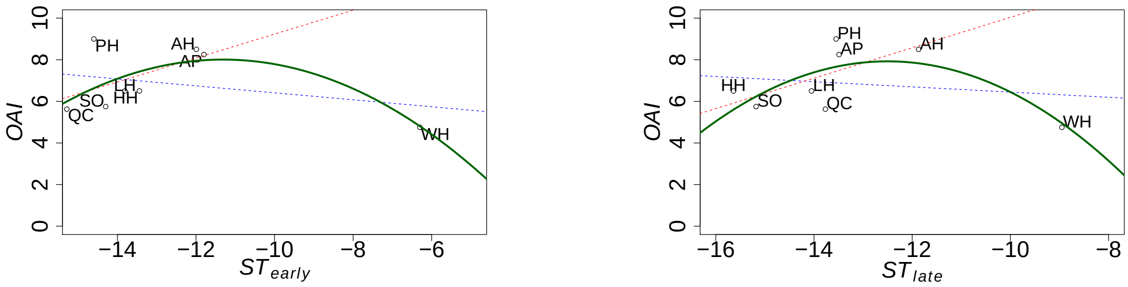
The well-established stage parameter ST_{early} has a possible optimum range for symphony orchestras between −13 to −11 dB according to Gade [1989c]. However, a possible optimum value for chamber music of −10 dB has been suggested by Gade [2007]. In this study values of ST_{early} (Figure 5.11) between −15 and −10 dB were observed on stage, with the exception of WH with an average ST_{early} value of −6.3 dB. WH is the only auditorium which is clearly outside the suggested optimum range for support, and this is reflected in the musicians' feedback. However, it is also evident that the support measures are unable to distinguish clearly the other seven auditoria from one another — even though musician feedback indicates there are distinct differences in the different stages/auditoria in terms of overall acoustic impression and ensemble.

ST_{early} is compared with median orchestra OAI in Figure 6.1a. A linear regression was examined and the correlation coefficient was found to be $r_l = -0.31$ ($p > 0.05$). To examine whether an improved linear relationship could be observed without WH (since WH has a very high value of ST_{early}) regression was also conducted excluding WH, and the correlation coefficient was found to be $r_l = 0.54$ ($p > 0.05$). Lastly, a quadratic regression was conducted, which accounts for WH, and gave a correlation coefficient of $|r_q| = 0.69$ ($p > 0.05$).

ST_{late} was also compared with median orchestra OAI in Figure 6.1b. The linear regression showed no relationship with WH included, but showed an improved fit with WH excluded $r_l = 0.65$ ($p > 0.05$). The quadratic regression also gave a reasonable, although non-significant, relationship ($|r_q| = 0.72$, $p > 0.05$). The quadratic regression indicates optimum ST_{late} may be a range between -13 and -12 dB for chamber orchestra musicians in purpose-built halls, although it should be noted that this quadratic relationship relies on WH (and with this hall excluded a linear relationship is more plausible).

Hidaka and Nishihara [2004] measured ST_{early} in 18 purpose-built chamber halls in Europe and Japan and found values between -12.8 and -4.4 dB, however subjective ratings were not obtained and results for ST_{late} were not presented. In a study of eight auditoria assessed by a symphony orchestra, Dammerud [2009] found no correlation between ST_{early} and OAI, whereas ST_{late} correlated with Rev (subjective reverberance) and OAI. Recent studies by others have also found ST_{early} does not correlate with subjective ratings [Cederlöf, 2006, Astolfi and Giovannini, 2007, Berntson and Andersson, 2007, van Luxemburg et al., 2009]. Lautenbach and Vercammen [2013] found weak correlations between ST_{early} and subjective characteristics when considering the 1 kHz octave band (rather than arithmetic average over 250–2000 Hz octave bands).

As an alternative to the ST parameters, Dammerud [2009] used modified version of sound strength G (including G_{7-50}, G_e and G_l) measured on stage. When considering these parameters Dammerud [2009] used source-receiver distances between 6–9 m and averaged over 500–2000 Hz octaves. In the present study source-receiver distances between 2.7 m and 6 m across-stage were used, as chamber orchestras were the focus. G_{7-50}, G_e and G_l vary de-



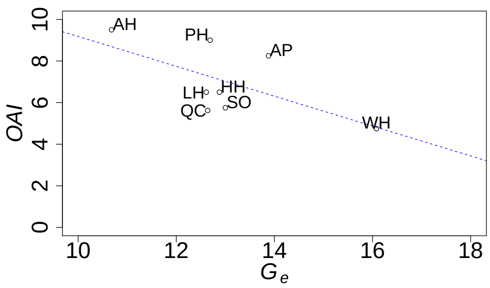
(a) OAI versus ST_{early}
$r_l = -0.31$ ($p > 0.05$)
$r_l = 0.54$ ($p > 0.05$) (excl WH)
$|r_q| = 0.69$ ($p > 0.05$)

(b) OAI versus ST_{late}
$r_l = -0.17$ ($p >0.05$)
$r_l = 0.65$ ($p >0.05$) (excl WH)
$|r_q| = 0.72$ ($p > 0.05$)

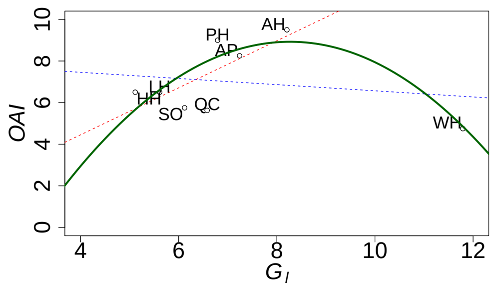
Figure 6.1: Orchestra median OAI compared to support measures arithmetically averaged over 250–2000 Hz octave bands. The data points are labelled with the auditorium identifiers. The curves represent linear (*dashed blue*), linear excluding WH (*dashed red*) and quadratic (*solid green*) regression curves, with the correlation coefficients r_l (linear regression) and $|r_q|$ (quadratic regression) indicated, and p value indicating level of significance.

pending on source-receiver distance (higher values with smaller source-receiver distance), and stage averaging has been avoided. A regression analysis has been used to compare median OAI with G_{7-50}, G_e and G_l. G_e is compared with median orchestra OAI in Figure 6.2a for the power average of the 2.7 m source-receiver distances, and also power averaged over 500–2000 Hz octave bands. The correlation coefficient was found to be $r_l = -0.63$ (p =0.09). The other source-receiver distances were also examined (4 m, 5.6 m and 6 m) and very similar results observed (r_l in a range between -0.57 and -0.63 and p in a range between 0.08 and 0.16). G_l is compared to median orchestra OAI in Figure 6.2b for the power average of 2.7 m source-receiver distances, and also power averaged over 500–2000 Hz octave bands. In this case linear and quadratic regressions are considered (as was required for ST_{late}). The linear regression shows no relationship, however the quadratic regression shows a reasonable fit ($|r_q| = 0.76$, $p = 0.13$). Again, the 4 m, 5.6 m and 6 m source-receiver distances were also considered and similar trends observed: no relationship for a linear regression and a reasonable relationship for a quadratic regression ($|r_q|$ between 0.58–0.74), however, all trends were non-significant. For G_l regression was also considered with WH removed and a linear trend observed ($r_l = 0.76$, p =0.06). Therefore the quadratic relationship is only observed when including WH (as was the case for ST_{late}). For median OAI and G_{7-50} no relationship was observed for any of the across-stage measurement distances. The findings in this study agree with Dammerud [2009], who also found G_l correlated well with subjective OAI (and subjective Rev). Dammerud also studied G_{7-50} and G_e for individual source-receiver paths (rather than stage averages), but found no clear trends with subjective ratings.

Based on the musicians' comments (Table 3.2) it appears the sound on-stage in WH was overly loud. Musicians' comments regarding WH included: *"It feels very live on the stage"* and *"Very loud!"*. This was observed objectively from both the ST parameters (higher values in WH compared to other halls) and from the modified versions of sound strength G (higher values in WH compared to others halls).



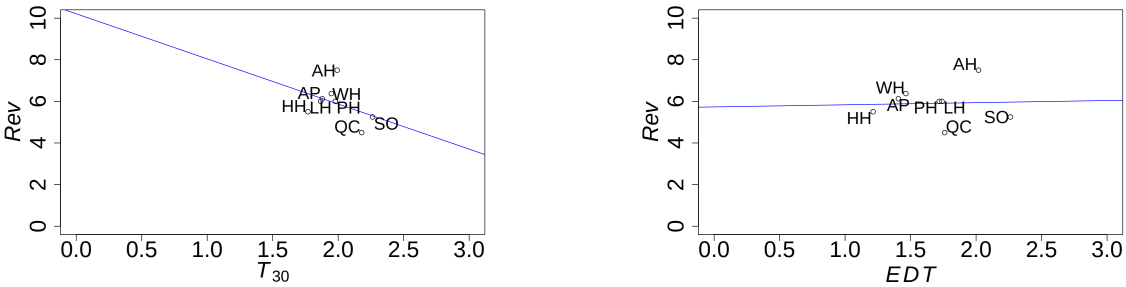
(a) OAI versus G_e
$r_l = -0.62$, $p = 0.09$



(b) OAI versus G_l
$r_l = -0.18$, $p > 0.05$
$r_l = 0.73$, $p = 0.06$ (excl WH)
$|r_q| = 0.76$, $p > 0.05$

Figure 6.2: Orchestra median OAI compared to G_e and G_l power averaged over 500–2000 Hz octave bands for 2.7 m source-receiver distances. The data points are labelled with the auditorium identifiers. The curves represent linear (*dashed blue*), linear excluding WH (*dashed red*) and quadratic (*solid green*) regression curves, with the correlation coefficients r_l (linear regression) and $|r_q|$ (quadratic regression) indicated, and p value indicating level of significance.

There was minimal variation observed in reverberation time (T_{30}) and early decay time (EDT) in the auditoria, and correspondingly the musicians' ratings indicated that subjectively there was little variation in reverberance. The median orchestra assessments for Rev (on a scale from 0–10) are in the range 4.5–6.4 for all auditoria, with the exception of AH, which was only slightly higher at 7.5. Recall that the subjective scale for reverberance was set up with optimum reverberance as 5 out of 10. In Figure 6.3a subjective reverberance was compared to stage T_{30} (500–2000 Hz average) and in Figure 6.3b subjective reverberance was compared to stage EDT (500–2000 Hz average). Unsurprisingly the relationships are non-significant in each case and the figures show the minimal variation in subjective reverberance and also in objective reverberation parameters. The importance of reverberance for musicians on stage should not be discounted, since this study of purpose-built halls included only halls with adequate reverberance. Others have consistently demonstrated the importance of reverberance to musicians playing on stage [Gade, 1989c, Sanders, 2003, Dammerud,



(a) Rev versus T_{30} (500–2000 Hz average) $r_l = -0.41$ ($p > 0.05$)

(b) Rev versus EDT (500-2000 Hz average), r_l =0.04 ($p > 0.05$)

Figure 6.3: Orchestra median Rev compared to reverberation parameters as measured on stage. The data points are labelled with the auditorium identifiers. The curves represent linear (*solid blue*), with the correlation coefficients r_l (linear regression) indicated, and p value indicating level of significance.

2009]. In Section 6.3, results are presented for ACO2 playing in multi-purpose halls which demonstrate a strong positive linear relationship between median Rev and T_{30}.

The results in this section suggest a possible quadratic relationship between OAI and the support parameters. Although, this was based on inclusion of WH, and by removing WH the relationship between OAI and support parameters becomes linear. G_e and G_l provided similar information to the ST parameters. The reverberation parameters (T_{30} and EDT) revealed little information about the halls in this dataset, however this is almost undoubtedly because there was minimal variation in T_{30} between the halls and similarly subjective reverberation (Rev) values showed little variation between halls in this dataset. In the purpose-built halls investigated in this study it appears most halls have acceptable levels of reverberance and support, which may actually act to disguise the relationship between subjective musicians' response and these well-known omnidirectional stage parameters. Additionally, omnidirectional parameters do not consider the directionality of on-stage sound fields, and parameters defined to assess on-stage directionality will be investigated in Section 6.2.2.

6.2.2 Spatial parameters

Based on previous studies, a relationship between musicians' ratings and spatial parameter defined to assess energy from 'above' relative to the 'sides' on stage was expected [Domínguez, 2008, Dammerud, 2009, Guthrie, 2014]. In particular, it was expected that lower values of the parameter TS_{20-50} (defined in Section 5.2.2) would correspond to higher ratings from musicians. From Figure 5.14 it appears that TS_{20-50} was low for the three best rated auditoria (PH, AH and AP), and higher for most of the other auditoria in the study. However QC appears to be an outlier in the dataset, where a low value of TS_{20-50} was not universally preferred; this result will therefore be discussed before presenting regression analyses on the full dataset.

In QC, the orchestra were not in consensus about the acoustics. QC was polarising, and while the majority of musicians rated it well, a small number gave very low scores on OAI (as low as 1/10, see Section 3.7). QC appears to have been disliked (by some) for other reasons which are not immediately apparent in our acoustic measurement data. Acoustic preference on stage is known to be multi-dimensional. This was explored in Section 3.6.1 with a principal component analysis to examine multidimensionality of the ACO dataset, which showed most of the subjective attributes contributing together to a principal component (highly correlated with OAI). Additionally, the omnidirectional parameters studied did not appear to indicate a reason for a number of poor musician ratings for QC either (see Section 6.2.1).

After considering the issues around the results for QC, a linear regression was performed to examine the relationship between TS_{20-50} and median OAI, but with the outlier QC excluded from the dataset. These regression analyses are shown in Figures 6.4a, 6.4b, 6.4c and 6.4d for the 250 Hz, 500 Hz, 1 kHz and 2 kHz octaves respectively. Additionally, the same results are shown in Figure 6.4e for TS_{20-50} power averaged over 250–2000 Hz octaves. For each data point the 1 m measurements at the four on-stage locations (positions S1–S4) were power averaged and the OAI ratings used were orchestra median values. With QC removed the linear regression is significant at a 5% level at 250 Hz, 500 Hz, 1 kHz and 2 kHz octave bands. The linear regression with QC included (not shown on the figures) is not significant at any octave band. It appears there may be a relationship between musicians' subjective preferences and the parameter TS_{20-50}, where lower values of TS_{20-50} are generally preferred. However, as discussed, QC is an outlier to this trend, where lower TS_{20-50} was not universally favoured by musicians.

It was also hypothesised that musicians orientated at some angle to the side walls may also benefit from early arriving energy from the 'back' region on stage. To test this hypothesis the median orchestra OAI has also been compared to a parameter TH_{20-50}, which includes sound energy from 'horizontal' (i.e. 'back' and 'sides'; note the 'front' region was excluded as it is open to the audience and would not provide sound energy over 20–50 ms). A comparison of

OAI and TH_{20-50} has been conducted. The TH_{20-50} parameter has been derived from the 1 m source-receiver pairs on stage, in the same manner as TS_{20-50}. In this case QC appeared to fit a linear trend reasonably well. Linear regression was conducted including and excluding QC (as QC was still considered a hall where musicians did not form a consensus). In Figure 6.5 the linear regression between median OAI and TH_{20-50} is significant at a 5% level (or lower) for each octave band between 250 and 2000 Hz and for the average over 250–2000 Hz octaves when QC is excluded. High correlation coefficients are also observed (between $r = 0.81$ and $r = 0.99$). When QC is included in the linear regression the relationship is still significant at each octave band at a 5% level (except for 2 kHz), and correlation coefficients are still high (between $r = 0.61$ and $r = 0.90$). It appears that QC, which was an outlier when examining TS_{20-50}, fits the expected trend reasonably well when examining TH_{20-50}. However the relationship does improve with the removal of QC and as discussed the stage acoustics in QC were polarising (well-rated by the majority but strongly disliked by some).

Overall, these results indicate it is worth considering 'horizontal' sound energy on stage (not just 'lateral' sound energy from the sides). This is a slightly different finding to past studies which have focused on a Top/Sides ratio. The present study is examining musicians' preferences on actual stages, whereas past studies have used laboratory conditions [Domínguez, 2008, Guthrie, 2014]. In the laboratory a musician would set up orientated forwards and sound energy arriving from the sides will be quite clearly defined, however on stage a musician may be orientated at an angle to the sides wall (i.e. facing towards the centre from the ensemble) and the 'sides' definition may no longer be as meaningful. Dammerud [2009] also found correlations between subjective characteristics and stage depth (D), which supports the importance of considering the 'back' region when examining directionality of on-stage sound fields.

In Section 5.3.5.1 the results for TS_{20-50} and TH_{20-50} were presented for SO with the acoustic cloud reflectors at chamber setting (approximately 9 m from stage) and highest setting (22 m from stage). The musicians' ratings obtained as part of the ACO tour were for the cloud reflectors at chamber setting. The ACO's preferred setting is the chamber setting. As intuitively expected, the cloud reflectors in place increases early energy from above (and therefore increases both TS_{20-50} and TH_{20-50}). The chamber setting also increases ST_{early} values (closer to the possible optimum observed in Section 6.2.1). Unfortunately, subjective musician testing was not obtained with and without the cloud reflectors in place, however based on the ACO's choice of setting in the hall it can be assumed the chamber setting would produce a higher OAI than with reflectors higher. Therefore, in this case higher values of

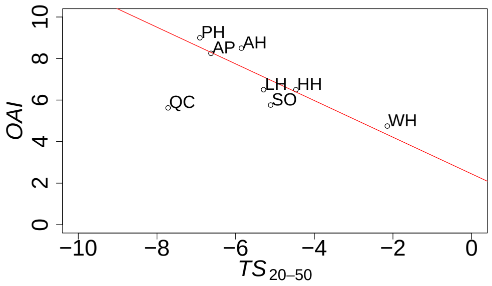
TS_{20-50} and TH_{20-50} may be preferred. This is not wholly unexpected because in cases where there is minimal early energy from the side early reflections from above may be preferred (and examining ST_{early} in conjunction with the spatial parameters can help to show this). The stage width in SO is 20.5 m. However this does not mean that early reflections from above create optimum conditions for the performer, and the orchestra median rating for SO was 5.8 (out of 10).

There are some reasons why horizontal reflections may be preferred over overhead reflections, although further research would be required to investigate these. In the broader field of auditorium acoustics from an audience perspective, lateral early reflections have been shown to contribute to auditory spatial impression (which is influenced by binaural dissimilarity) [Okano et al., 1998], and it is conceivable that there is an analogous enhancement of sound quality from lateral reflections on stage. On stage, horizontal reflections are subject to scattering through the ensemble, which ameliorates or avoids simple comb filter effects (as shown in Chapter 4). Additionally the direct sound (which, by the 'precedence effect' or 'Haas effect' [Kuttruff, 2007], is important in localising the sound source) arrives in the horizontal plane. In addition to the direct sound, early reflections are known to be beneficial for ensemble and a reflection will fuse better with the direct sound when arriving from a direction close to that of the direct sound, as discussed by others [Litovsky et al., 1999, Dammerud, 2009].

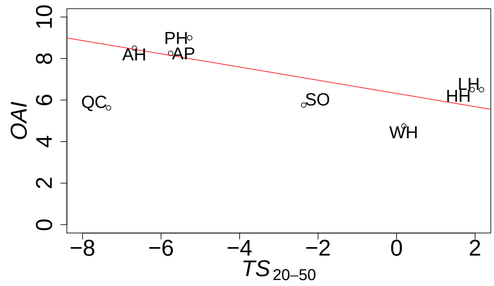
6.2.3 Architectural measures

In this section regression analysis has been performed between orchestra median overall acoustic impression (OAI) and key architectural measures. The comparisons are presented in Figure 6.6. Note the correlation is provided with and without QC, as was done for the parameters TS_{20-50} and TH_{20-50} (see earlier discussion around QC in Section 6.2). Recall, W is width to side reflecting surfaces, H is the height from stage to above reflecting surfaces and D is the stage depth.

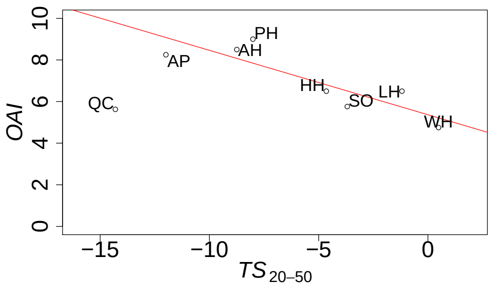
Median OAI compared H/W gives a significant relationship ($r_l = 0.78$, $p < 0.05$) when QC is excluded. However, when QC is included the relationship is not significant. This agrees with the findings for the spatial parameter TS_{20-50}, and from Section 5.6.2 there is a strong relationship between H/W and TS_{20-50}. The positive linear correlation coefficient (r_l) between



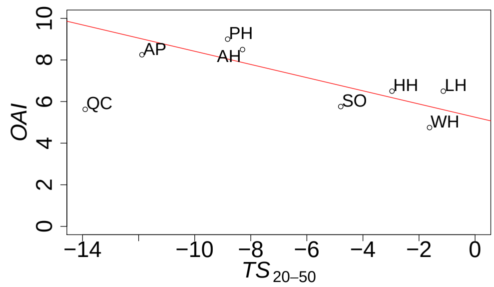
(a) TS_{20-50} (250 Hz), $r_l = 0.89$, $p < 0.01$



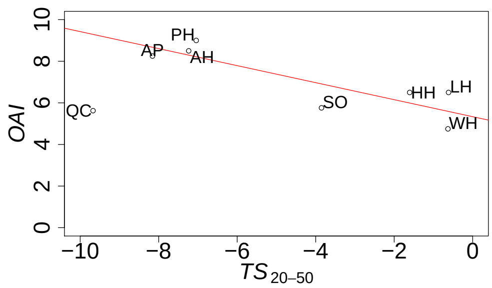
(b) TS_{20-50} (500 Hz), $r_l = 0.75$, $p = 0.05$



(c) TS_{20-50} (1 kHz), $r_l = 0.87$, $p = 0.01$

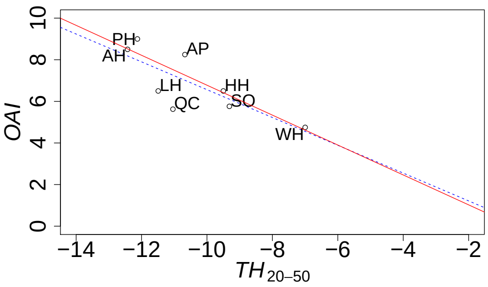


(d) TS_{20-50} (2 kHz), $r_l = 0.82$, $p = 0.02$

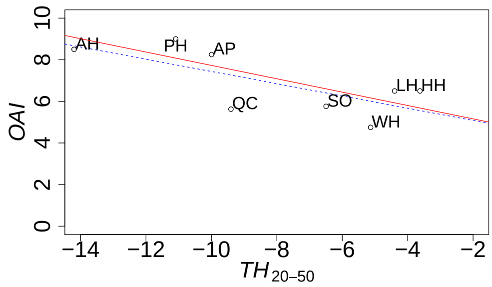


(e) TS_{20-50} (250–2000 Hz), $r_l = 0.86$, $p = 0.01$

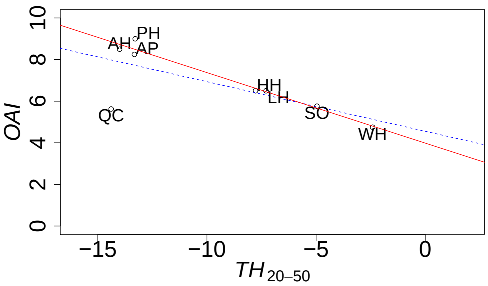
Figure 6.4: Orchestra median OAI compared to TS_{20-50} power averaged over positions 1–4 at each octave band. Note: the data points are labelled with the auditorium identifiers. Linear regression (*solid red*) excludes QC. The p value indicates level of significance.



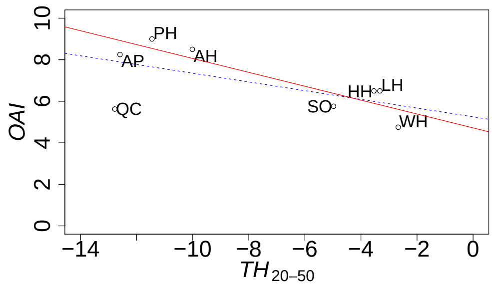
(a) TH_{20-50} (250 Hz)
$r_l = 0.87$, $p < 0.05$ (excl QC)
$r_l = 0.77$, $p = 0.01$ (incl QC)



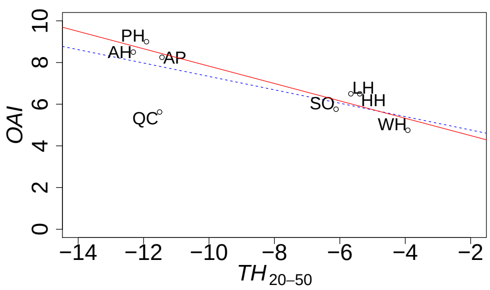
(b) TH_{20-50} (500 Hz)
$r_l = 0.81$, $p < 0.05$ (excl QC)
$r_l = 0.90$, $p < 0.05$ (incl QC)



(c) TH_{20-50} (1 kHz)
$r_l = 0.99$, $p < 0.01$ (excl QC)
$r_l = 0.72$, $p < 0.05$ (incl QC)



(d) TH_{20-50} (2 kHz)
$r_l = 0.90$, $p < 0.01$ (excl QC)
$r_l = 0.61$, $p > 0.05$ (incl QC)



(e) TH_{20-50} (average 250-2000 Hz)
$r_l = 0.95$, $p < 0.01$ (excl QC)
$r_l = 0.74$, $p < 0.05$ (incl QC)

Figure 6.5: Orchestra median OAI compared to TH_{20-50} power averaged over positions 1–4 at each octave band. Note: the data points are labelled with the auditorium identifiers. Linear regression (*solid red*) excludes QC. Linear regression (*dashed blue*) includes QC. The p value indicates level of significance.

median OAI and H/W indicates a preference for high and narrow stage enclosures. This agrees with findings from Dammerud [2009] when studying stage enclosures for symphony orchestras.

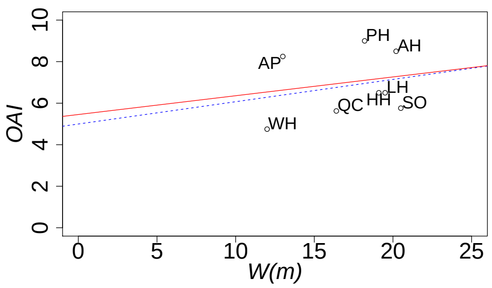
Median OAI compared to H is also significant with QC excluded ($r_l = 0.92$, $p < 0.01$). This is not the case for W or D where there is basically no relationship with OAI. However, median OAI compared to $H/\sqrt{D.W}$ is highly significant excluding QC (and the relationship is still evident when QC is included). This agrees with the findings for the spatial parameter TH_{20-50}, and from Section 5.6.2 there is a strong relationship between $H/\sqrt{D.W}$ and TH_{20-50}. The positive linear correlation coefficient (r_l) between median OAI and $H/\sqrt{D.W}$ indicates a preference for "horizontal" reflections from the stage enclosure (either stronger or earlier than reflections from above). A ratio of stage depth to stage width was also investigated (D/W) but showed no relationship to median OAI.

The architectural measures presented here can be easily measured for simple stage enclosures (i.e. shoe-box stage enclosures). For more complex stage enclosure designs the spatially-defined acoustic parameters may be advantageous as they don't rely on simple relationships between height above stage and stage width/depth.

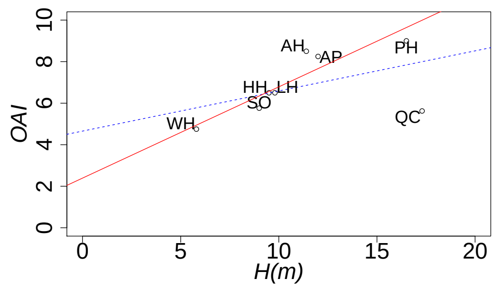
6.2.4 Summary of subjective and objective relationships: ACO

A summary of the key relationships between subjective ratings and objective measures is provided in Table 6.1. In all cases linear correlation coefficients (r_l) have been provided. For the ST parameters the linear regression is given with and without WH (since WH did not fit the linear trend of the other halls). For comparison quadratic correlation coefficients ($|r_q|$) are also provided. Also note that as discussed earlier, for spatial parameters regression has been considered with and without QC.

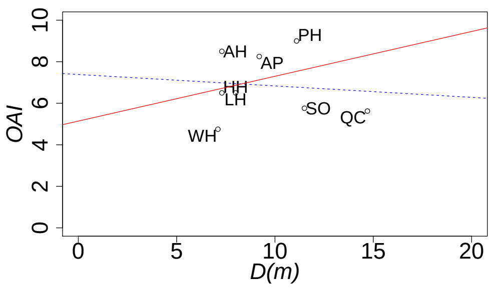
As stated in Section 6.2, there was no relationship between reverberation parameters (T_{30} and EDT) and subjective reverberance (Rev), however this was attributed to close-to-optimum reverberance in each hall in the dataset. Overall, Table 6.1 shows a quadratic relationship between musicians' ratings and the support measures, however it should be noted that the quadratic relationship relies on the inclusion of WH (which was a small stage and had high values of ST_{early} and ST_{late}). Additionally, the stages in this study mostly had values of ST close to proposed optimum values by Gade [1989c], which partly explains the quadratic relationships observed near the optimum. It may also explain why correlations between musicians' ratings and ST parameters are non-significant, since it is difficult to observe a relationship when for most stages the support parameters are adequate. Table 6.1 shows



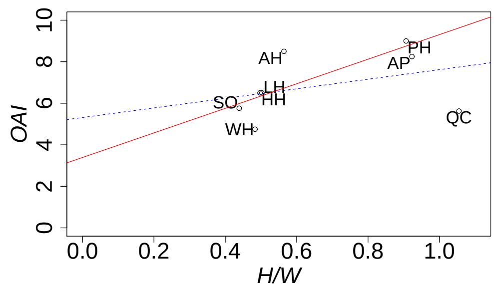
(a) W
$r_l = 0.20$, $p > 0.05$ (excl QC)
$r_l = 0.22$, $p > 0.05$ (incl QC)



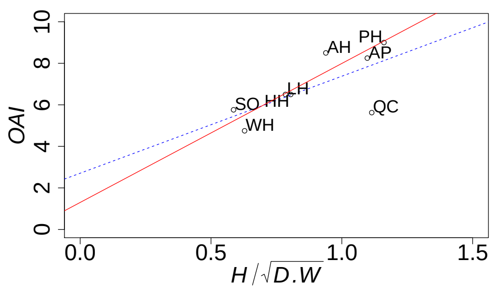
(b) H
$r_l = 0.92$, $p < 0.01$ (excl QC)
$r_l = 0.48$, $p > 0.05$ (incl QC)



(c) D
$r_l = 0.25$, $p > 0.05$ (excl QC)
$r_l = -0.10$, $p > 0.05$ (incl QC)



(d) H/W
$r_l = 0.78$, $p = 0.04$ (excl QC)
$r_l = 0.37$, $p > 0.05$ (incl QC)



(e) $H/\sqrt{D.W}$
$r_l = 0.93$, $p < 0.01$ (excl QC)
$r_l = 0.68$, $p = 0.07$ (incl QC)

Figure 6.6: Orchestra median *OAI* compared to architectural measures. Note: the data points are labelled with the auditorium identifiers. Linear regression (*solid red*) excludes QC. Linear regression (*dashed blue*) includes QC. The p value indicates level of significance.

that parameters assessing the directionality of on-stage sound fields are the most subjectively relevant for this dataset, and often the relationship between OAI and the spatially-defined stage parameters (or architectural measures) are significant.

Table 6.1: Correlation coefficients for linear regression (r_l) and quadratic regression ($|r_q|$) between subjective orchestra median OAI and acoustic stage parameters or architectural measures. Bold numbers indicate significance at the 1% and underlined at the 5% level. In some cases regression without WH or QC have been investigated. Also note, the quadratic regression has been considered for the ST parameters (due to WH) . Total number of samples $N = 8$.

Parameter	r_l	$\|r_q\|$
$ST_{early}{}^{*}$	$-0.31(0.54^{a})$	0.69
$ST_{late}{}^{*}$	$0.17(0.65^{a})$	0.72
$G_e{}^{\diamond}$	0.62	
$G_l{}^{\diamond}$	$0.18(0.73^{a})$	
$TS_{20-50}{}^{\star}$	$-0.51(\underline{-0.85}^{b})$	
$TH_{20-50}{}^{\star}$	$\underline{-0.74}$ $(\mathbf{-0.95}^{b})$	
H/W	$0.37(\underline{0.78}^{b})$	
$H/\sqrt{D.W}$	$0.68(\mathbf{0.93}^{b})$	

* 1 m S-R dist, 250–2000 Hz octave band average (arithmetic)
$^{\diamond}$ 2.7 m S-R dist, 500–2000 Hz octave band average (power)
* 1 m S-R dist, 250–2000 Hz octave band average (power)
[a] WH excluded
[b] QC excluded

The relationships between objective measures and other key subjective attributes, namely Reverberance (Rev), Ensemble (Ens), Support (Sup) and Timbre (Tim), are also presented here. These results are summarised in Table 6.2. This analysis has been conducted for completeness, however the following should be noted: 1) high correlation coefficients were observed between overall acoustic impression (OAI) and these key subjective attributes (r between 0.68–0.73 and all significant at a 1% level) and 2) past studies have indicated musicians tend to have difficulties assessing auditoria on *multiple* scales [Chiang et al., 2003].

In Table 6.2 linear correlation coefficients (r_l) are given for subjective characteristics and ST_{early} and ST_{late}, as well as the corresponding quadratic correlation coefficients ($|r_q|$). In the case of linear regression, the correlations coefficients with WH excluded are also provided. Recall from Section 6.2, high values of ST_{early} and ST_{late} were observed in WH (and musicians indicated the sound on stage was too loud). With WH removed commonly weak linear relationships are seen between ST parameters and musicians' ratings. Including WH and considering quadratic regression the correlation is often quite high, although the relationships between subjective attributes and ST parameters are all non-significant. This is not necessarily unexpected given the minimal variation in ST parameters within the dataset and the sample size.

Table 6.2: Correlation coefficients for linear regression (r_l) and quadratic regression ($|r_q|$) between subjective orchestra median attributes and objective stage parameters. For ST parameters regression without WH has been investigation. For spatial parameters regression without QC has been investigated. Bold numbers indicate significance at the 1% and underlined at the 5% level.

	r_l		$\lvert r_q \rvert$		r_l	
Var.	ST_{early}	ST_{late}	ST_{early}	ST_{late}	TS_{20-50}	TH_{20-50}
OAI	−0.31(0.54[a])	−0.17(0.65[a])	0.69	0.72	−0.51 (**−0.85**[b])	$\underline{-0.74}$ (**−0.86**[b])
Rev	0.52($\underline{0.72}$[a])	0.54(0.60[a])	0.79	0.61	0.11 (−0.37[b])	−0.15 (−0.51[b])
Ens	0.02(0.45[a])	0.02(0.10[a])	0.60	0.40	−0.33 (**−0.89**[b])	−0.53 (**−0.92**[b])
Sup	0.14(0.46[a])	0.19(0.37[a])	0.60	0.49	−0.08 (−0.61[b])	$\underline{-0.74}$ (**−0.95**[b])
Tim	−0.15(0.37[a])	−0.12(0.13[a])	0.67	0.42	−0.09 (−0.68[b])	−0.38 ($\underline{-0.84}$[b])

[a] WH excluded
[b] QC excluded

In Table 6.2 the linear correlation coefficients (r_l) are also given for subjective characteristics and TS_{20-50} and TH_{20-50}. The parameter TS_{20-50} correlates well with subjective ensemble (Ens) when QC is excluded, however this is not observed with QC included. The parameter TH_{20-50} appears to be more subjectively relevant than TS_{20-50}, and correlates well with all subjective attributes (except Rev).

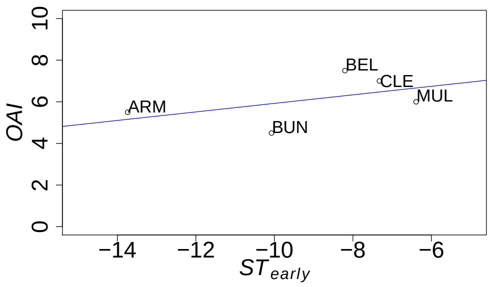
6.3 Subjective and objective results: Auditoria assessed by ACO2

The ST parameter (ST_{early} and ST_{late}) were compared to median overall acoustic impression (OAI) for the auditoria assessed by ACO2. A non-significant relationship was observed between OAI and ST_{early} ($r_l = 0.50$) as shown in Figure 6.7a. The correlation between OAI and ST_{late} was strong ($r_l = 0.93$, $p = 0.02$) as shown in Figure 6.7b.

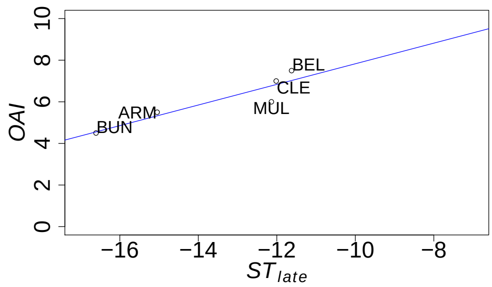
Subjective reverberance (median Rev) was compared to reverberation parameters. In Figure 6.8a, the relationship between median Rev and stage T_{30} (500–1000 Hz octave average) was significant ($r_l = 0.92$, $p < 0.05$), where in Figure 6.8b the relationship between median Rev and stage EDT (500-1000 Hz octave average) was non-significant.

ST_{late} was also highly correlated with median Rev ($r_l = 0.92$, $p < 0.05$), median Tim

($r_l = 0.96$, $p < 0.01$), median Ens ($r_l = 0.98$, $p < 0.01$) and median Sup ($r_l = 0.76$, $p > 0.05$). Similarly, T_{30} was also highly correlated with median OAI ($r_l = 0.95$, $p = 0.01$), median Tim ($r_l = 0.96$, $p < 0.05$), median Ens ($r_l = 0.96$, $p < 0.01$) and Sup ($r_l = 0.76$, $p > 0.05$). Overall, for ACO2 it appears that most of the subjective assessments can be related to late reverberant sound on stage (as assessed by T_{30} and ST_{late}). This is expected because in this dataset there was a high correlation between overall acoustic impression and reverberance ($r = 0.75$, $p < 0.01$). This contrasts with the auditoria assessed by ACO, where adequate support and reverberance were observed in most halls. It is also clear that for the ACO2 dataset a quadratic regression is not necessary between ST_{late} and OAI. This is because there are no halls in the dataset where ST_{late} values are particularly high, and therefore it is not possible to deduce an optimum ST_{late} from this data.

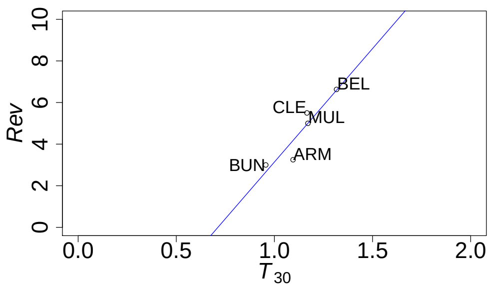


(a) OAI versus ST_{early}
$r_l = 0.50$ ($p > 0.05$)

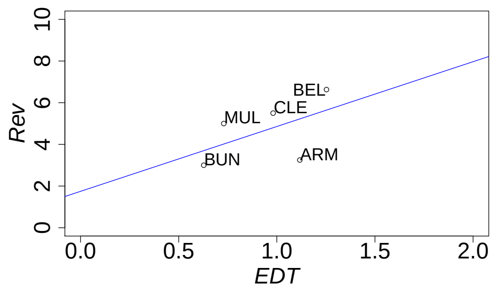


(b) OAI versus ST_{late}
$r_l = 0.93$ ($p = 0.02$)

Figure 6.7: Orchestra median OAI compared to support measures arithmetically averaged over 250–1000 Hz octave bands. The data points are labelled with the auditorium identifiers. The curve represents linear regression, with the correlation coefficients r_l (linear regression) indicated and p value indicating significance.



(a) Rev versus T_{30} (500-1000 Hz)
$r_l = 0.93$ ($p < 0.05$)



(b) Rev versus EDT (500-1000 Hz)
$r_l = 0.53$ ($p > 0.05$)

Figure 6.8: Orchestra median Rev compared to reverberation parameters. The data points are labelled with the auditorium identifiers.

6.4 Limitations

In this study musicians' questionnaires were labelled with a musician ID, so that if needed individual musicians' trends could be investigated. To account for individual musician responses a mixed model (multilevel model) would be needed. In this work such a model has not been implemented and individual musician trends have been effectively ignored. A visual inspection was used to examine whether the intercept and slope appeared to vary between musicians when comparing objective data and subjective responses (as this would point towards a mixed model being needed), but general agreement was seen in both intercept and slope across musicians. In QC most musicians gave positive ratings but a small number gave particularly low ratings. However since QC was the only auditorium where this occurred, a mixed model does not appear necessary (since a mixed model assumes an individual is consistently assessing in a different manner, such as consistently positive or consistently negative in all halls). In the other halls the standard deviation of musicians' ratings (from ACO) was low (see Figure 3.3).

Correlation analysis was used for the ACO and ACO2 datasets, which contained eight auditoria ($N = 8$) and five auditoria ($N = 5$) respectively. The sample size in each case was dictated by the number of halls visited by the orchestras, and the number of halls which would be acoustically measured. These sample sizes are similar, or slightly higher, than past studies, however due to the subjective nature of acoustics on stage for musicians (and the confounding factors involved) higher sample sizes would be preferable. For regression analysis a sample size of at least 10 would be preferable [Field et al., 2012]. In Appendix C chamber ensemble musicians' ratings were compared to the data from ACO, to verify the findings from ACO, and the sample size was effectively increased to nine or ten halls ($N = 9 - 10$) and visually excellent agreement was observed between ACO and the chamber ensembles.

In this study the data from each chamber orchestra was analysed separately, however a possible extension to the work would be to pool the chamber orchestra datasets (and potentially also include the chamber ensemble data). In this case a mixed model analysis would be needed to control for the hierarchical nature of the data (i.e. individual musicians contained within different orchestras). However, such an analysis would benefit from more subjective musician data and more acoustic measurements, particularly if factors like instrument were to be investigated.

6.5 Conclusions

In this chapter musicians' impressions and acoustic stage measurements have been compared. For the ACO dataset ST_{early} and ST_{late} showed relationships with musicians' preferences when considering quadratic regressions. However it must be noted the quadratic regressions relied on WH and when WH was excluded weak linear regressions were obtained. For ACO playing in purpose-built concert halls, there were adequate levels of reverberance making it difficult to observe the relationship between musicians' rating and omnidirectional parameters assessing reverberance (such as T_{30} and EDT). Others have also observed that the importance of reverberance can be disguised when only halls with optimum reverberance are included in the dataset [Sanders, 2003, Dammerud, 2009]. In the multi-purpose auditoria assessed by ACO2 some halls had inadequate levels of support and reverberance, and ST_{late} and T_{30} were found to be highly correlated with musicians' ratings.

For the ACO dataset a relationship was observed between musicians' preferences and the spatial distribution of early energy on stage. There was a preference for horizontal sound energy on stage (i.e. from the enclosure walls) rather than energy from above (i.e. from the ceiling). This finding is also reinforced by the chamber ensemble data, see Appendix C. Additionally, simple architectural measures (defined to assess directionality of on-stage sound fields) also showed significant relationships to musicians' ratings. This was expected since the architectural measures and spatially-defined acoustic parameters were highly correlated in the halls in this study. Correlations between the spatially-defined acoustic parameters and architectural measures will be strongest when stage enclosures are "shoe-box" shaped. Stage measurements with a spherical microphone array are particularly useful to assess the directionality of on-stage sound fields for more unusual stage enclosure shapes.

Chapter 7

Overall discussion and conclusions

This study has investigated stage and auditorium acoustics for chamber orchestra musicians using subjective surveying, modelling, and physical acoustic measurements. The key findings of this dissertation are discussed here.

Subjective experience of musicians on stage

Survey results were obtained from three chamber orchestras and three chamber ensembles, and the musicians took questionnaires on tours. This helped to control for factors such as musician's position on stage, instrument, playing experience and acoustical memory. However, not all the limitations of in situ musician surveying could be eliminated, such as musician bias towards halls (such as based on past playing experiences). There were high response rates from the surveys conducted, showing the interest the musicians took in stage and auditorium acoustics. Additionally, many musicians included detailed and insightful written comments. The chamber orchestra and ensemble musicians' responses consistently revealed that the four subjective acoustic attributes most highly correlated with overall acoustic impression were: (1) 'Support' (2) 'Ensemble' (3) 'Reverberance' and (4) 'Timbre'. This result agrees with previous studies of musicians' experiences [Gade, 1981, Sanders, 2003]. It should be noted that for one tour (the Australian Chamber Orchestra in purpose-built auditoria) the correlation between overall acoustic impression and reverberance was notably lower. The explanation for this is that in these purpose-built halls, with near optimal reverberation time, there was minimal variation in subjective reverberance.

Effect of chamber orchestra on on-stage sound fields

A chamber orchestra was modelled with boundary element method (BEM), and validated against hemi-anechoic chamber and auditorium measurements with seated and standing musicians. The agreement between BEM model results and measurements results demonstrated the BEM model produced realistic results. Three source-receiver distances within the model orchestra were investigated, examining direct sound (and floor reflection) and first-order enclosure reflections individually. The source-receiver height used was 1.5 m for the predominantly standing chamber orchestra, which differs from previous studies of on-stage attenuation which have used a seated orchestra (and 1.2 m receiver height) [Dammerud et al., 2010, Wenmaekers et al., 2016].

For the 250 Hz octave band and above the chamber orchestra affected the on-stage sound fields and the empty stage and occupied stage conditions were notably different. The effect of the orchestra on ceiling reflections was consistently low. The effect of the orchestra on horizontal reflections was dependent on source-receiver path, particularly for 250 Hz and 500 Hz octave bands where the destructive interference between direct sound and floor reflection was most prominent (and affected by the orchestra's presence). A tilted wall case was also studied which found that for a modest angle the effect of the orchestra significantly reduced.

Quantifying stage acoustics with objective parameters

Acoustic measurements on 15 stages were conducted to explore via correlations how the subjective experience of on-stage sound fields for chamber orchestra musicians could be objectively quantified with acoustic parameters. The standard omnidirectional parameters (T_{30}, EDT, ST_{early}, ST_{late}, G_e and G_l) were examined, as well as newly proposed spatially-defined stage parameters (TS_{20-50} and TH_{20-50}) and also architectural measures designed to infer the directionality of on-stage sound fields.

In the ACO dataset, with purpose-built concert halls, ST_{early} was correlated weakly with overall acoustic impression when considering a quadratic regression ($r_q = 0.69$, $p > 0.05$), and indicated an optimum ST_{early} value of around-12 dB on stage for chamber orchestra musicians. ST_{late} was correlated weakly with overall acoustic impression when considering a quadratic regression ($r_q = 0.72$, $p > 0.05$), and indicated an optimum ST_{late} value of between -13 and -12 dB on stage for chamber orchestra musicians. However, the quadratic relationships observed relied on the inclusion of Wollongong Town Hall, and when excluding this hall the ST parameters appeared to show weak linear relationships to OAI. In the ACO2 dataset, with multi-purpose halls with inadequate reverberance included, high correlations were observed between overall acoustic impression and both T_{30} ($r_l = 0.93$, $p < 0.05$) and ST_{late} ($r_l = 0.92$, $p < 0.05$). In these halls it appears much of the subjective assessment was related to level of reverberant (or late) sound in the halls, which has been shown to be subjectively important to musicians consistently in the literature [Sanders, 2003, Dammerud, 2009].

Spatial analysis of on-stage sound fields was explored in eight auditoria assessed by ACO. The energy from early reflections from above (such as ceiling reflections) was compared to early horizontal reflected energy (such as from stage enclosure walls). Two spatially defined stage parameters were explored: TS_{20-50} (comparing early energy from 'top' to energy from 'sides') and TH_{20-50} (comparing early energy from 'top' to from 'horizontal'). Both parameters showed strong relationships to subjective assessments. In particular TH_{20-50} correlated highly with overall acoustic impression ($r_l = -0.74$, $p < 0.05$). This indicates musicians prefer early lateral or horizontal sound energy relative to sound energy from above, as found in a number of past studies assessing the directionality of on-stage sound fields for musicians [Domínguez, 2008, Dammerud, 2009, Guthrie, 2014]. It appears that early reflections from above (such as from a ceiling reflector) cannot fully compensate for a lack of early lateral energy on stage, as found by Dammerud et al. [2011]. Architectural measures accounting for the directionality of on-stage sound fields were also explored, and were shown to correlate with overall acoustic impression. Architectural measures offer a simple way of estimating the likely directionality of on-stage sound fields and may provide some guidance at the very earliest design phase, however measurements with a spherical microphone array are more appropriate for stages with complex enclosures.

The results of this study appear to indicate that for chamber orchestras first optimum reverberance on stage is important, followed by the level of early sound energy on stage and finally the spatial distribution of this early energy. This study also found that the importance of adequate reverberance and support may be disguised where only purpose-built halls with adequation on stage reverberance and support are considered.

Overall conclusions

The use of a spherical microphone array to assess spatial distribution of on-stage sound fields was found to be a useful addition to the standard omnidirectional analysis. This study is one of the first to assess the directionality of on-stage sound fields, using in situ musician surveying and in situ measurements. The findings appear to indicate the direction of very early sound energy on stage is subjectively important, and that musicians may have a preference for early horizontal sound energy on stage rather than sound energy from above. A parameter to assess sound energy from the above compared to from enclosure walls was proposed and correlated with overall acoustic impression. Stage parameters defined to assess late or reverberant sound on stage (T_{30} and ST_{late}) also correlated with musicians' ratings, as found in past studies [Gade, 1989c, Sanders, 2003, Dammerud, 2009].

The work on the effect of a chamber orchestra on on-stage sound fields demonstrated some significant differences between the occupied and empty stage situation for a chamber orchestra (and thus undoubtedly for a larger ensemble as well). Stage measurements without the orchestra present can be thought to give an indication of the on stage acoustic conditions but are likely to miss the finer details of the experience for musicians on stage, particularly in terms of ensemble and timbre. The destructive interference between direct sound and floor reflection was shown to be reduced by the presence of a chamber orchestra on stage, whereas discrete ceiling reflections were not affected by the orchestra but were shown to suffer from comb-filtering. This highlights possible benefits from scattering by ceilings, and also suggests the preference for early horizontal stage enclosure reflections could relate to the timbre of the sound on stage. Occupied stage measurements would be preferable to assess early sound on stage and timbre on stage, although they are commonly seen as too expensive and time consuming to be consistently conducted. Computer modelling of orchestra is likely to be a more realistic way to assess occupied stages in the future.

Future work

The survey methods in this study ensured that the same musicians completed the ratings in different auditoria to allow valid comparisons to be made. This is recommended as a model for future studies, particularly for studies of chamber orchestra or ensemble musicians where tours of the same repertoire in multiple halls are relatively common. Additionally, a larger sample size is always preferable. Studies with fewer than five halls have commonly been non-conclusive [Cederlöf, 2006, Astolfi et al., 2007]. Future studies should aim to collect high quality subjective musician data in at least 8 to 10 halls. Additionally, in future work the data collected from the three chamber orchestras and the three chamber ensembles could be pooled into a larger dataset and compared to acoustic measurements. This would be most beneficial if further acoustic measurements were obtained, and also if further chamber musician surveying was conducted. A larger dataset would then make a mixed model analysis useful to explore factors such as which ensemble a musician performed with and instrument.

The BEM model of a chamber orchestra offers an accurate way to investigate the effect of an orchestra on on-stage sound fields, and additionally BEM offers flexibility in what can be studied and how the results can be presented. The main limitation of BEM modelling is the computational intensity. In future increased computing power could allow higher frequencies to be explored or equally BEM modelling of a larger symphony orchestra. In this study BEM modelling has been a tool to explore the effect of the chamber orchestra with angle of the arriving reflection, however the investigation was limited to first-order reflections, and future work could consider more complex sound fields.

This study has suggested a preference for lateral or horizontal stage enclosure reflections (as opposed to reflections from above), however further work is needed to confirm this relationship. It has been suggested that this may be because reflections arriving predominately in the horizontal plane are useful for ensemble, and also may be preferred in terms of timbre, however the exact mechanism behind this preference cannot be fully explored with an in situ field study. Future work in the laboratory could focus on whether the timing or strength of early reflections from 'above' and from the 'sides' (and/or 'back') is more important. Lastly, the time limits used in the spatial parameters should be further explored, as it is not possible to conclude from this study whether the time window used for the spatial parameters is most subjectively relevant to musicians.

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Appendix A

Published work

The results in this disseration have been published as a peer-reviewed journal articles (see Panton et al. [2016] and Panton et al. [2017]). Preliminary results from this research project are included in the following peer-reviwed conference articles: Panton and Holloway [2014], Panton et al. [2015], Panton and Holloway [2015], Panton et al. [2016a] and Panton et al. [2016b]. For full versions of journal articles refer to publishers. The conference papers are included in full in this appendix for reference.

A.1 Journal Article 1

Stage Acoustics in Eight Australian Concert Halls: Acoustic Conditions in Relation to Subjective Assessments by a Touring Chamber Orchestra

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Acoustics Australia

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Abstract

Although auditorium acoustics has been extensively studied from an audience perspective, studies of musicians' preferences on stage are far more limited. The present work tests and extends the hypothesis, suggested in recent studies by others, that the directional distribution of early-reflected energy on stage is subjectively important to musicians. The paper presents results of subjective surveys completed by musicians of the Australian Chamber Orchestra (ACO) immediately after performing in eight Australian purpose built concert halls, and compares these with complementary on-stage acoustic measurements undertaken in the same eight auditoria using a 32-channel spherical microphone array (Eigenmike). Spatial acoustic parameters are investigated together with the traditional omnidirectional parameters defined in the international standard for auditorium acoustics measurements, and a parameter is proposed that compares early energy arriving on stage from above relative to the sides. The parameter is shown to correlate well with musicians' subjective ratings, with generally lower values preferred. By contrast, standard omnidirectional parameters provided only limited insights into musician preferences for the eight auditorium stages surveyed.

A.2 Journal Article 2

Effect of a chamber orchestra on direct sound and early reflections for performers on stage: A Boundary Element Method study

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The Journal of the Acoustical Society of America

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Abstract

Early reflections are known to be important to musicians performing on stage, but acoustic measurements are usually made on empty stages. This work investigates how a chamber orchestra setup on stage affects early reflections from the stage enclosure. A boundary element method (BEM) model of a chamber orchestra is validated against full scale measurements with seated and standing subjects in an anechoic chamber and against auditorium measurements, demonstrating that the BEM simulation gives realistic results. Using the validated BEM model, an investigation of how a chamber orchestra attenuates and scatters both the direct sound and the first-order reflections is presented for two different sized shoe-box stage enclosures. The first-order reflections from the stage are investigated individually: at and above the 250 Hz band, horizontal reflections from stage walls are attenuated to varying degrees, while the ceiling reflection is relatively unaffected. Considering the overall effect of the chamber orchestra on the direct sound and first-order reflections differences of 2–5 dB occur in the 1000 Hz octave band when the ceiling reflection is excluded (slightly reduced when including the unobstructed ceiling reflection). A tilted side wall case showed the orchestra has a reduced effect with a small elevation of the lateral reflections.

A.3 Conference Paper 1

A BEM study of the influence of musicians on onstage sound field measures in auditoria

Lilyan Panton[1], and Damien Holloway[1]

[1]School of Engineering and ICT, University of Tasmania

Internoise 2014, Melbourne, Australia

16–19 November 2014

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A.4 Conference Paper 2

Investigating concert hall acoustics from musicians' perspective: Summary of results from a survey of two touring chamber orchestras

Lilyan Panton[1], Damien Holloway[1] and Densil Cabrera[2]

[1]School of Engineering and ICT, University of Tasmania [2]Faculty of Architecture, Design and Planning, University of Sydney

Acoustics 2015, Hunter Valley, Australia

15–18 November 2015

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A.5 Conference Paper 3

A BEM study on the effect of source-receiver path route and length on attenuation of direct sound and reflection within a chamber orchestra

Lilyan Panton[1], and Damien Holloway[1]

[1]School of Engineering and ICT, University of Tasmania

Acoustics 2015, Hunter Valley

15–18 November 2015

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A.6 Conference Paper 4

Using a spherical microphone array for stage acoustics: A preliminary case for a new spatial parameter

Lilyan Panton[1], Damien Holloway[1] and Densil Cabrera[2]

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ICA 2016, Buenos Aires, Argentina

5–9 September 2016

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A.7 Conference Paper 5

Overview and preliminary results from a study of stage acoustics for chamber orchestras

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ISMRA 2016, Buenos Aires, Argentina

11–12 September 2016

Appendix B

Survey results with chamber ensembles

Subjective surveying was conducted with three chamber ensemble groups during 2016, with the assistance of Musica Viva Australia. This data was collected to allow a comparison with ratings from larger chamber orchestras. The auditoria subjectively assessed by chamber ensembles include many of those which were surveyed by ACO, as well as others.

The full list of auditoria assessed by at least one chamber ensemble is: Perth Concert Hall (PH), City Recital Hall Angel Place Sydney (AP), Adelaide Town Hall (AH), Queensland Conservatorium Theatre Brisbane (QT), Melbourne Recital Centre (MC), Hobart Town Hall (HT), Llewellyn Concert Hall (LH), Harold Lobb Concert Hall Newcastle (HL), Armidale Town Hall (ARM) and Lecture Theatre D, Coffs Harbour Education Campus (CH).

To ensure musicians remain anonymous the name of the ensemble will not be provided when discussing the chamber ensembles; instead the first chamber ensemble discussed will be referred to as Chamber Ensemble 1, the second chamber ensemble will be referred to as Chamber Ensemble 2, and the third chamber ensemble will be referred to as Chamber Ensemble 3. The chamber ensemble musicians completed the questionnaires on tour (consistent repertoire played in auditoria) and the survey method (and questionnaire itself) was the same as that used with the chamber orchestra musician surveying. The ensembles were international touring groups, hence would not be familiar with the auditoria.

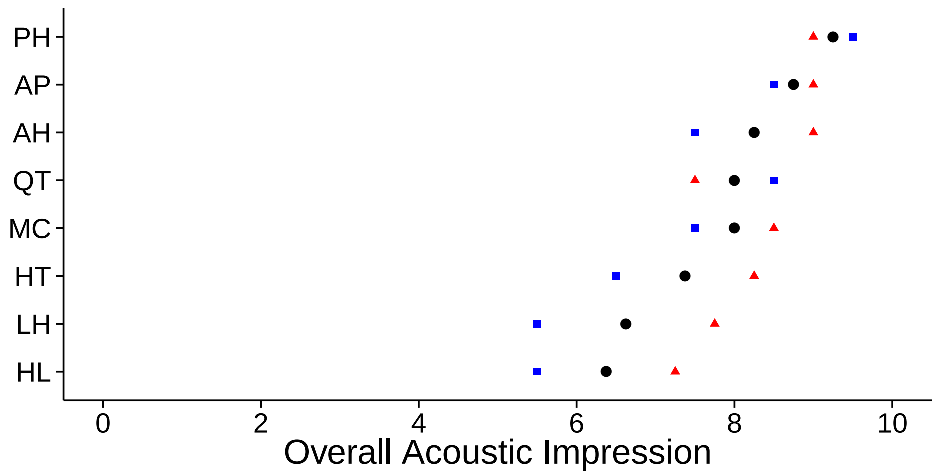


Figure B.1: Mean 'overall acoustic impression' (OAI) for Chamber Ensemble 1 (black circle), with the respondents 1 and 2 shown separately (blue square and red triangle).

In Figure B.1 the mean OAI is shown from Chamber Ensemble 1, the number of respondents from this ensemble was two musicians ($N = 2$). Since there were two respondents in this case, showing a standard deviation would not be meaningful and instead the respondents individual results are presented to demonstrate the agreement. In Figure B.2 the mean results for all subjective characteristics for Chamber Ensemble 1 are presented. The comments from musicians in Chamber Ensemble 1 are included in Table B.1. The most preferred auditorium for Chamber Ensemble 1 was PH. Although almost all auditoria were given positive ratings on average (>6 out of 10). PH was clearly a very well-liked auditorium, the average score on OAI was 9.25 out of 10. In terms of 'Rev' (subjective reverberance) for PH the average score was 3.5 out of 10 (which is noticeably lower than the other auditoria in Figure B.2); however, one respondent actually gave PH a score of 5.5 out of 10 (close to the optimum position of 5) and one respondent gave PH a score of 1.5 out of 10 (indicating it was dry on-stage). The respondent who gave PH 1.5 out of 10 (indicating dry on stage) added the comment *"Dry on stage, yet warm and reverberant in audience - great combo"* (as shown in Table B.1), actually indicating that the auditorium itself was not overly dry and also indicating a preference for low subjective reverberance on stage. Therefore the low score for 'Rev' in Figure B.2 should not be misinterpreted as a negative rating.

In Figure B.3 the results for all subjective characteristics for a Chamber Ensemble 2 are presented, in this case there was only one respondent meaning there was no averaging required. The most preferred auditorium was HT, and AH and AP were also highly rated. The least preferred auditorium was CH, which was highly disliked. However, this auditorium was a

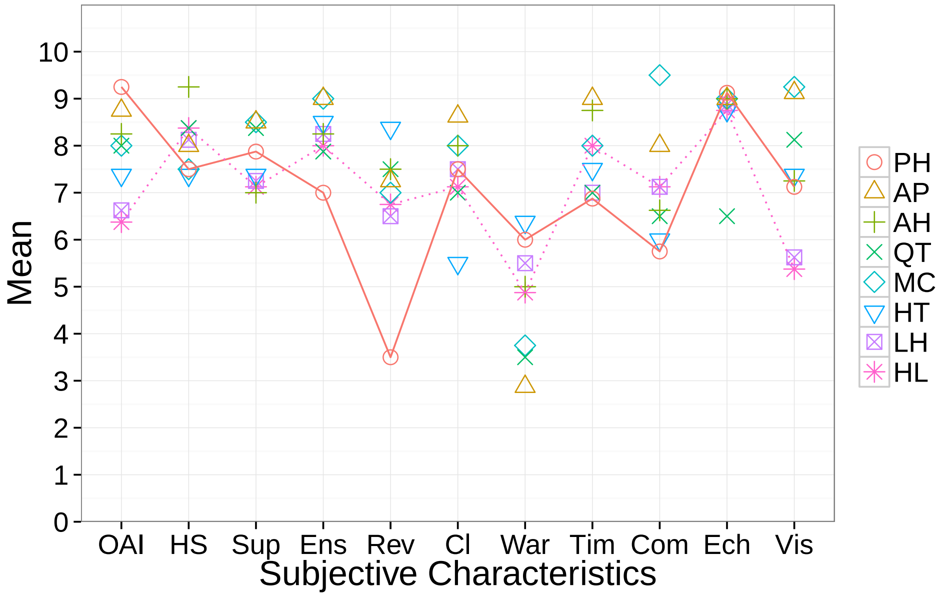


Figure B.2: Average assessments for subjective characteristics in auditoria, for Chamber Ensemble 1 (with sample size $N = 2$). A solid line is shown through the data for the highest rated auditorium (PH) and a dashed line through the data for the lowest rated auditorium (HL).

Table B.1: Comments from musicians regarding on-stage acoustics in auditoria for Chamber Ensemble 1 tour

Auditorium	Comments
PH	'Enjoyed this hall. A little clearer on stage than others, and making us listen more/differently.' 'Dry on stage, yet warm and reverberant in audience - great combo'
AP	'Fantastic Hall. Being picky, it seemed that the lower end register of the cello didn't have as much help as upper registers/other instruments.'
MC	'Sounds from audience are loud! Distracting... shame, because otherwise it's a stunning hall. 2nd performance: much improved, quieter audience during playing' 'Too easy to hear audience - a little distracting'
HT	'Very nice hall, although a shame it isn't isolated (traffic noise)"

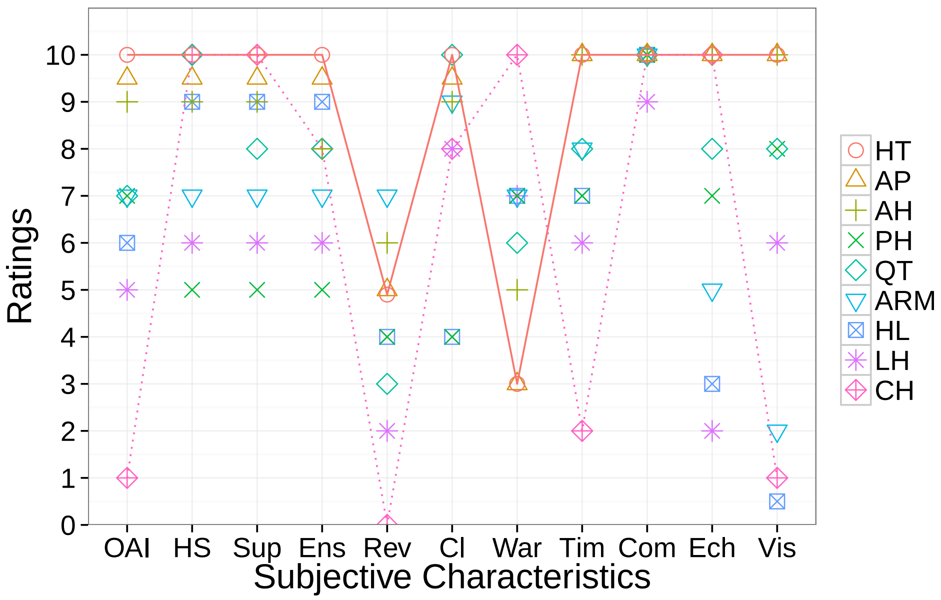


Figure B.3: Ratings for subjective characteristics in auditoria, for Chamber Ensemble 2 (with sample size $N = 1$). A solid line is shown through the data for the highest rated auditorium (HT) and a dashed line through the data for the lowest rated auditorium (CH).

lecture theatre not designed for the performance of music.

In Figure B.4 the results for all subjective characteristics for a Chamber Ensemble 3 are presented, in this case there was only one respondent meaning there was no averaging required. In this dataset there are only four auditoria. MC was the most preferred, closely followed by AH and PH, whereas LH was rated far lower.

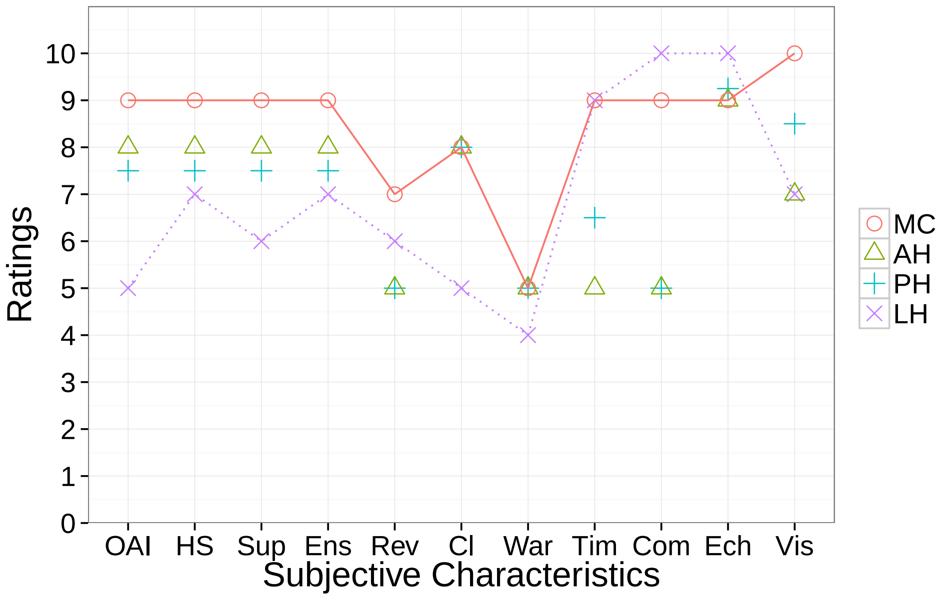


Figure B.4: Ratings for subjective characteristics in auditoria, for Chamber Ensemble 3 (with sample size $N = 1$). A solid line is shown through the data for the highest rated auditorium (MC) and a dashed line through the data for the lowest rated auditorium (LH).

Appendix C

Auditoria assessed by chamber ensembles: comparison of subjective and objective results

Subjective musician data was collected from several chamber ensembles regarding auditoria already discussed in relation to ACO, as well as other auditoria. When comparing this data to stage measurements there are a number of inherent issues:

(1) The sample size in each case was one or two respondents (for chamber ensembles with a total of between 2–4 players). If a single musician had any kind of personal bias towards an auditorium this would become highly influential to the dataset. Additionally, biased responses will not be identified in the dataset, as there is not enough data to compare to a group average.

(2) The responses from musicians' were consistently positive (see Appendix B). This may be because the acoustical demands on the musicians were less in these smaller groups (particularly in terms of "ease of ensemble"). However from the ACO auditoria we note that the well-rated auditoria were generally included in the chamber ensemble tours (i.e. PH, AH and AP).

However, the data from chamber ensembles can be used to validate the assessments given by the ACO, and in this section the chamber ensembles ratings will discussed in comparison to the ACO dataset. In many cases halls were assessed by both ACO and at least one chamber ensemble. The chamber ensemble results will be presented individually to highlight agreement with ACO.

C.1 Chamber Ensemble 1

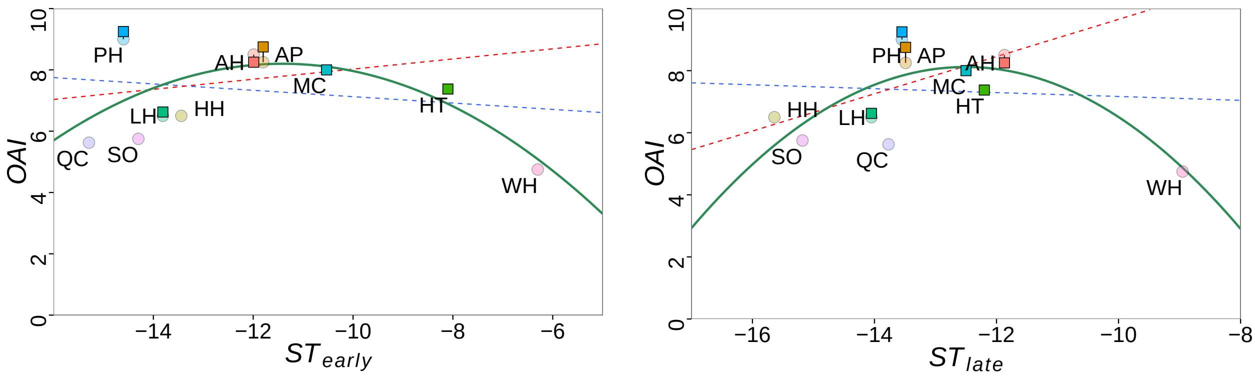
This dataset included six auditoria which have been acoustically measured (PH, AP, AH, MC, HT and LH) and two auditoria (QT and HL) which were not measured (auditoria identifiers are detailed in Appendix B). The best-rated auditoria by both respondents were PH and AP, closely followed by AH and MC and HT. As we have seen from the ACO dataset (Section 6.2.1) PH, AP and AH were universally well-rated, and have adequate reverberance and support. Likewise, MC was also a well-rated auditoria (average OAI of 8 out of 10) as was HT (average OAI of 7.4 out of 10). LH was rated only slightly lower (average OAI of 6.6 out of 10).

In Figure C.1a the results for mean OAI from Chamber Ensemble 1 and ST_{early} on stage are compared to the same results from the ACO dataset (previously presented in Figure 6.1a). This demonstrates the remarkable agreement between the chamber ensemble's average OAI ratings and median OAI ratings by ACO. The chamber ensemble data helps to demonstrate a quadratic relationship between OAI and ST_{early} since the two additional auditoria (MC and HT) fit the quadratic regression curve based on the ACO data. This supports an optimum ST_{early} value close to $-12\,\mathrm{dB}$ for chamber ensemble and orchestra musicians. PH is still shown to be an outlier with the ratings from Chamber Ensemble 1 included.

In Figure C.1b the results for mean OAI from Chamber Ensemble 1 and ST_{late} on stage are compared to the same results from the ACO dataset (previously presented in Figure 6.1b). A possible quadratic regression between OAI and ST_{late} (with optimum value of ST_{late} between -13 and $-12\,\mathrm{dB}$) is presented, however it must be noted that this quadratic relationship is based only on WH and with this hall removed a linear relationship becomes more plausible.

In Figure C.2a the results for mean OAI from Chamber Ensemble 1 and TS_{20-50} (250–2000 Hz average) on stage are compared to the same results from the ACO dataset (previously presented in Figure 6.4e). In Figure C.2b the results for mean OAI from Chamber Ensemble 1 and TH_{20-50} on stage are compared to the same results from the ACO dataset (previously presented in Figure 6.5e). The data from Chamber Ensemble 1 supports the linear relationships between OAI and TS_{20-50} and between OAI and TH_{20-50} established with the ACO dataset. As discussed previously, QC (from the ACO dataset) is a notable outlier from the trend. However, unfortunately QC was not assessed by any chamber ensemble.

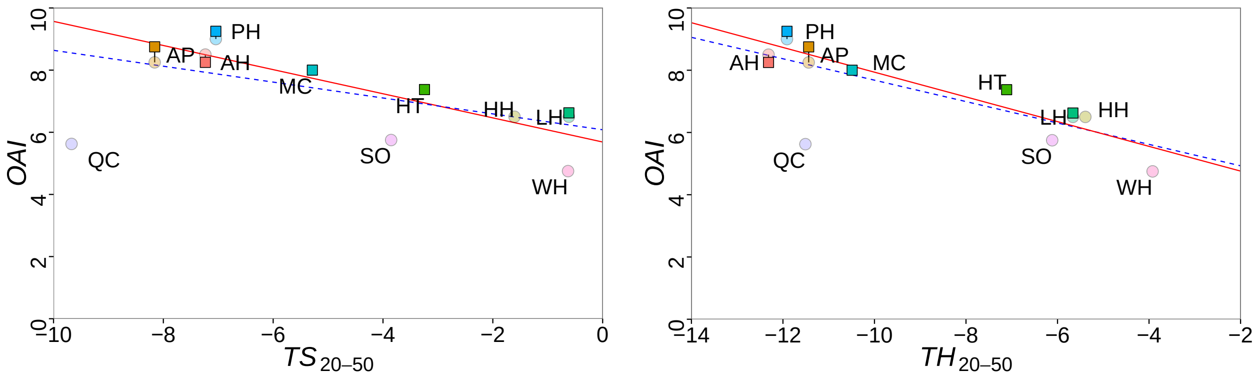
In Figures C.2a and C.2b three auditoria sit a little below the trend line: QC, SO and WH. This could be because of the results for ST_{early} in these halls as shown in Figure C.1a. In QC, SO and WH ST_{early} values are away from the optimum which may have led to slightly lower ratings on OAI than would be expected based on TS_{20-50} and TH_{20-50} only.



(a) OAI versus ST_{early}

(b) OAI versus ST_{late}

Figure C.1: OAI versus ST parameters where solid squares indicate average OAI for Chamber Ensemble 1 (2 respondents) and transparent circles indicate median OAI for ACO (15 respondents). The data points are labelled with the auditorium identifiers (the same auditoria are connected by a solid black line). The linear (*dashed blue*) and quadratic (*solid green*) lines are based on ACO and Chamber Ensemble 1 data pooled, whereas the linear (*dashed red*) line is ACO and Chamber Ensemble 1 data but excludes WH.



(a) OAI versus TS_{20-50}

(b) OAI versus TH_{20-50}

Figure C.2: OAI versus spatially-defined stage parameters (averaged over 250–2000 Hz octaves) where solid squares indicate average OAI for Chamber Ensemble 1 (2 respondents) and transparent circles indicate median OAI for ACO (15 respondents). The data points are labelled with the auditorium identifiers (the same auditoria are connected by a solid black line). The linear (*solid red*) regression line excludes QC. The linear (*dashed blue*) regression line includes QC.

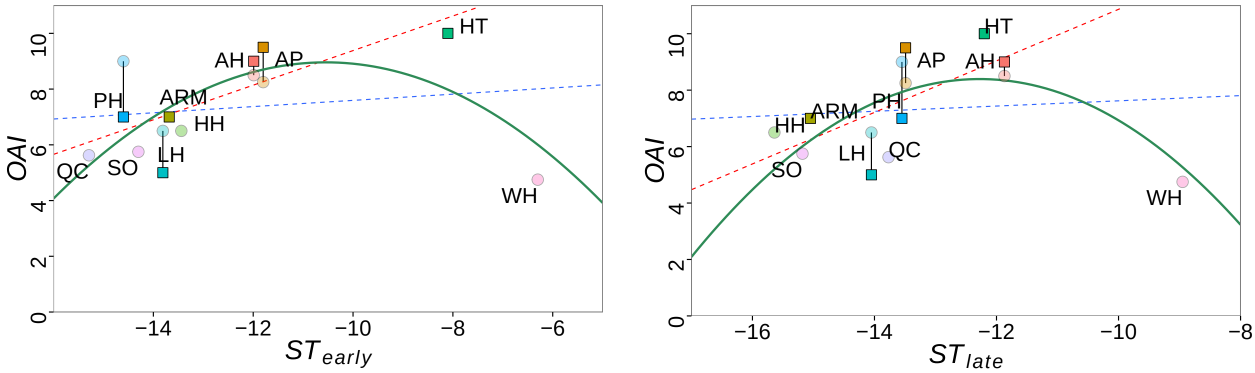
C.2 Chamber Ensemble 2

This dataset included six auditoria which have been acoustically measured (HT, AP, AH, PH, ARM and LH) and three auditoria (QT, HL and CH) which were not measured (auditoria identifiers are detailed in Section B). The best-rated auditoria by the single respondent were HT, AP and AH (ratings >9 out of 10), followed by PH and ARM (both rated 7 out of 10). LH was rated 5 out of 10.

In Figure C.3a the results for OAI from the single respondent from Chamber Ensemble 2 and ST_{early} on stage are compared to the same results from the ACO dataset (previously presented in Figure 6.1a). There is good agreement between the OAI ratings from the single respondent from Chamber Ensemble 2 and median OAI ratings by ACO, though not as close for Chamber Ensemble 1. Similarly, in Figure C.3b the results for OAI from the single respondent from Chamber Ensemble 2 and ST_{late} on stage are compared to the same results from the ACO dataset (previously presented in Figure 6.1b). For both ST parameters a quadratic relationship (relying on the hall WH) is presented, as well as the linear relationship with WH removed.

In Figure C.4a the results from Chamber Ensemble 2 and TS_{20-50} (250–2000 Hz average) on stage are compared to the same results from the ACO dataset (previously presented in

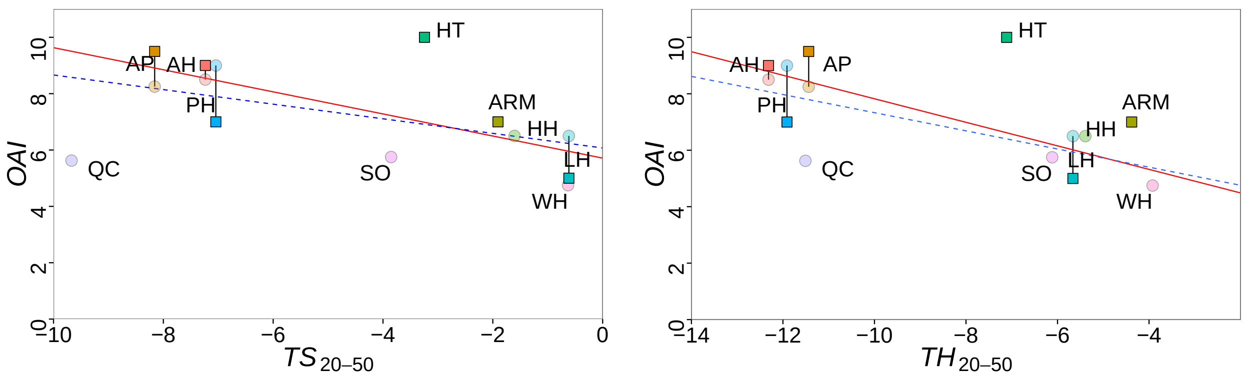
Figure 6.4e), and in Figure C.4b the results for OAI from Chamber Ensemble 2 and TH_{20-50} on stage are compared to the same results from the ACO dataset (previously presented in Figure 6.5e). These figures support linear regressions between OAI and TS_{20-50} and between OAI and TH_{20-50}, with lower values preferred in both cases.



(a) OAI versus ST_{early}

(b) OAI versus ST_{late}

Figure C.3: OAI versus ST parameters where solid squares indicate average OAI for Chamber Ensemble 2 (1 respondents) and transparent circles indicate median OAI for ACO (15 respondents). The data points are labelled with the auditorium identifiers (the same auditoria are connected by a solid black line). The linear (*dashed blue*) and quadratic (*solid green*) lines are based on ACO and Chamber Ensemble 1 data pooled, whereas the linear (*dashed red*) line is ACO and Chamber Ensemble 1 data but excludes WH.



(a) OAI versus TS_{20-50}

(b) OAI versus TH_{20-50}

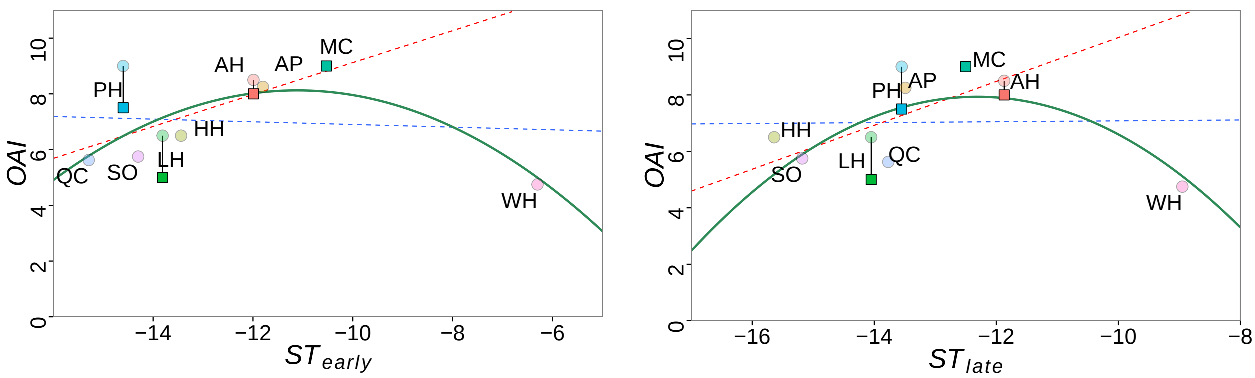
Figure C.4: OAI versus spatially-defined stage parameters (averaged over 250–2000 Hz octaves) where solid squares indicate average OAI for Chamber Ensemble 2 (1 respondents) and transparent circles indicate median OAI for ACO (15 respondents). The data points are labelled with the auditorium identifiers (the same auditoria are connected by a solid black line). The linear (*solid red*) regression line excludes QC. The linear (*dashed blue*) regression line includes QC.

C.3 Chamber Ensemble 3

This dataset included four auditoria which have all been acoustically measured (PH, AH, MC and LH), and recall three of these halls were also assessed by ACO (PH, AH and LH). The single respondent highly rated MC, AH and PH (ratings between 7.5–9 out of 10), whereas LH was rated 5 out of 10.

In Figure C.5a the results for OAI from the single respondent from Chamber Ensemble 3 and ST_{early} on stage are compared to the same results from the ACO dataset (previously presented in Figure 6.1a), and in Figure C.5b the results for OAI from the single respondent from Chamber Ensemble 3 and ST_{late} on stage are compared to the same results from the ACO dataset (previously presented in Figure 6.1b). Again a linear regression is considered (excluding WH) and a quadratic regression is considered (including WH). Again good agreement is seen between this single respondent from Chamber Ensemble 3 and ACO in terms of OAI.

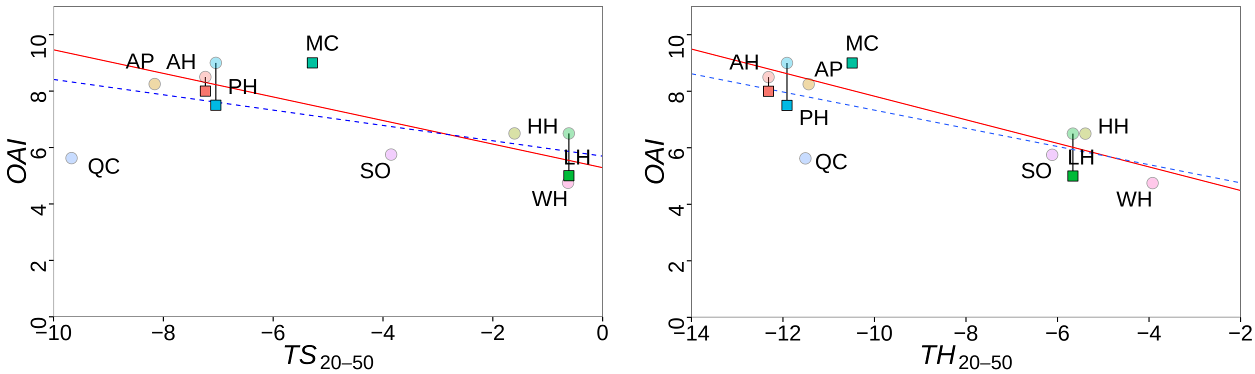
Figures C.6a and C.6b show the same comparison as Figures C.4a and C.4b, but for the single respondent from Chamber Ensemble 3. Like the earlier figures these support the proposed linear regressions.



(a) OAI versus ST_{early}

(b) OAI versus ST_{late}

Figure C.5: OAI versus ST parameters where solid squares indicate average OAI for Chamber Ensemble 3 (1 respondents) and transparent circles indicate median OAI for ACO (15 respondents). The data points are labelled with the auditorium identifiers (the same auditoria are connected by a solid black line). The linear (*blue dashed*) and quadratic (*green solid*) regression lines are based on ACO data only ($N = 8$).



(a) OAI versus TS_{20-50}

(b) OAI versus TH_{20-50}

Figure C.6: OAI versus spatially-defined stage parameters (averaged over 250–2000 Hz octaves) where solid squares indicate average OAI for Chamber Ensemble 3 (1 respondents) and transparent circles indicate median OAI for ACO (15 respondents). The data points are labelled with the auditorium identifiers (the same auditoria are connected by a solid black line). The linear (*solid red*) regression line excludes QC. The linear (*blue dashed*) regression line includes QC.

C.4 Conclusion

Overall, the results from the chamber ensembles showed excellent agreement with the results for ACO. Additionally, the chamber ensembles visited a number of extra halls, not assessed by ACO. In most cases the subjective ratings of OAI and the support parameters (ST_{early} and ST_{late}) in these additional halls fitted the linear regression curves from the ACO dataset (with WH excluded). Similarly, the relationships between chamber ensemble ratings and the spatially-defined parameters (TS_{20-50} and TH_{20-50}) also showed good agreement with ACO results. The chamber ensemble musicians preferred lower values of these parameters, indicating a preference for horizontal or lateral sound energy on stage.

Appendix D

BEM model of a chamber orchestra

In this appendix the validation undertaken for the BEM model discussed in Chapter 4 is summarised. The BEM analysis was conducted using FastBEM ®. To ensure accurate results, a mesh size of at least an eighth of a wavelength was always used. FastBEM offers a full boundary element method solver, which solves the full Helmholtz equations, and accelerated methods. In this work the adaptive cross approximation (ACA) solver, which uses a hierarchical matrix partitioning structure, has been used.

To validate their scale model, Dammerud and Barron [2010] tested a simplified configuration and compared results to unpublished full scale measurements undertaken by Krokstad et al. [1980], and matched the absorption for the scale model musicians to the absorption found in full scales measurements by Harwood et al. [1972] A more recent study by Jang and Jeon [2016] also examined absorption of seated musicians in a reverberation chamber, and found some variation depending on factors like clothing type, instruments and seating density, nevertheless overall good agreement was observed with Harwood et al. [1972]. Krokstad's full scale measurements with seated musicians involved a simplified case of two lines of seated people (one line with six people and one line with five people) in front of a source. The difference in sound pressure level (SPL) between a receiver placed behind the last person (8 m from the source) and a reference receiver at 1 m from the source was investigated. Three source heights were used (0.6 m, 0.9 m and 1.3 m) and average results from three source heights were presented in 1/3 octaves. The loudspeaker type used in measurements by Krokstad is unknown. Krokstad also did not provide any information on the precise location of the musicians between the source and the 8 m microphone, and did not state whether the measurements were undertaken in a room where surface reflections could impact the results. Despite these potential sources of error and ambiguity, Dammerud and Barron states that the scale model results were within +1 and −2 dB at 1 kHz and 2 kHz compared to the measurements by Krokstad et al. [1980]. However, Dammerud and Barron do not provide information on the agreement at other frequencies. Due to the ambiguity surrounding the measurement procedure used by Krokstad (and use of frequency averaging and source-receiver height averaging), a similar experimental setup has been recreated in the present study to provide a stronger basis for model validation.

The authors replicated Krokstad's measurements in a hemi-anechoic chamber (using 6 seated subjects, rather than the 11 used by Krokstad). Sound propagating around standing people was also investigated because chamber orchestras frequently perform with musicians (violins and violas) standing. The 6 seated or standing subjects were arranged as shown in Figure D.1. The room's anechoic lining is specified as such at and above the 200 Hz 1/3-octave band. The chamber internal dimensions (from the faces of the lining) are 6.5 m × 3.6 m × 3.0 m (vertical). A miniature (0.1 m diameter) dodecahedral loudspeaker (type Dr Three) was used as the source. This loudspeaker qualifies as omnidirectional according to ISO3382-1 criteria over the measurement frequency range, with deviations within ±1 dB up to the 2 kHz 1/3-octave band. The receivers were omnidirectional microphones (1/2 inch diameter Brüel&Kjær type 4190). The difference in sound pressure level (SPL) between the 5.5 m microphone and reference microphone was investigated. Both the seated and standing musicians were modelled in Autodesk Inventor® using combinations of simple geometries to allow for easy meshing.

The ACA solver was compared to conventional BEM solution over 125–1000 Hz for the validation setup (Figure D.1) with excellent agreement found. All further solves were then conducted with the ACA solver for faster solution times.

Impedance was initially specified in the BEM model based on the equivalent absorption areas selected by Dammerud and Barron [2010] for their scale model. Dammerud and Barron measured these equivalent absorption areas for the model musicians in a scale reverberation chamber, and matched them as closely as possible to the full scale absorption areas for musicians measured in a full sized reverberation chamber by Harwood et al. [1972].

Equivalent absorption areas can be related to an absorption coefficient by dividing by the object surface area. This relationship is only strictly valid when the absorption coefficient

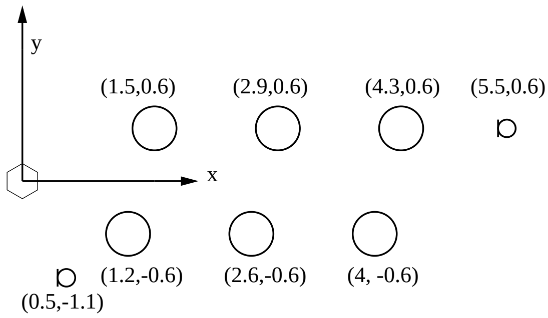


Figure D.1: Setup of seated musicians in the hemi-anechoic chamber. The coordinates (in m) specified for each musician refer to the centre of the back of the musician's chair. The source was located at the origin of the coordinate system. Also shown are the 5.5 m microphone and the reference microphone. The same configuration was used for standing musicians, however in that case the coordinates refer to the approximate centre point of each standing musician. The source and receiver heights were respectively 0.8 m and 1.2 m for seated tests, and 1.0 m and 1.5 m for standing tests.

of a large flat sample of a material is being measured in a reverberation chamber. Although Dammerud and Barron measured absorption area in a reverberation chamber, model musicians were three-dimensional hence the use of this data to obtain absorption coefficients is only approximate. The seated and standing model musicians have an approximate surface area of 2 m^2 each.

The absorption coefficients were then converted to impedance values. Equivalent absorbing area (or the corresponding absorption coefficients) only provide information regarding the change in amplitude of the sound wave once reflected by the object, not the change in phase. The reflection coefficient was assumed to be positive and real (i.e. $R = \sqrt{1-\alpha}$). An imaginary component of the reflection coefficient implies some change in phase — significant phase change generally only occurs when the absorbing layer is thick compared with the wavelength, or has an air gap behind it (which may be the case for clothing in some cases). However, in previous investigations improved agreement with full scale measurements were not found from introducing a significant phase change [Panton and Holloway, 2014]. In the absence of a rational basis for defining an imaginary part of the complex impedance it was set to zero.

Table D.1 summarises the absorption area per musician from Dammerud and Barron's scale model, the equivalent absorption coefficients, and the corresponding reflection factor magnitude and complex impedance. A quadratic curve was fitted to these data for absorption area

Table D.1: Absorption area, absorption coefficients, corresponding reflection coefficients and impedance values applied to surfaces of seated musicians based on Dammerud and Barron's absorption areas.

Octave (Hz)	125	250	500	1000	2000
A (m^2)	0.07	0.24	0.41	0.7	0.86
α	0.03	0.12	0.2	0.35	0.43
$\|R\|$	0.98	0.94	0.89	0.81	0.76
Z_s (kg/m^2s)	46547	12981	7241	3870	2975

(A) versus frequency, so that the impedance values were gradually changed with frequency.

As well as the seated musicians, impedance values had to be applied to music stands. Absorption coefficients based on 1 cm thick plywood taken from Cox and D'Antonio [2009], see Table D.2. Again, the reflection coefficient (R) was assumed to be real and positive, and this time an exponential curve was a better fit to α to avoid jumps in results due to an abrupt change in impedance in each octave band. The music stands were modelled as just the music stand face, without a 'pole', because the slender pole would require a fine mesh (and large number of elements) to model but would not significantly impact the sound fields under 2000 Hz. Music stands are not included in the validation setup (Figure D.1), however they are included in the final chamber orchestra model (Section 4.2.1).

Impedance values up to 2000 Hz were defined for the purposes of curve fitting, although computations were only conducted up to the upper end of the 1000 Hz octave since the next octave required a four-fold element number increase and was not feasible for the final orchestra model.

To compare the results from the full scale measurements and the BEM model a quantity $\Delta L_{5.5\,\mathrm{m\,-\,ref}}$ was defined as the difference in SPL between the 5.5 m receiver and the reference receiver, see Eq. D.1. The precise receiver locations for the these receivers are shown in Figure D.1.

$$\Delta L_{5.5\,\mathrm{m\,-\,ref}} = \mathrm{SPL}_{5.5\,\mathrm{m}} - \mathrm{SPL}_{\mathrm{ref}} \tag{D.1}$$

When considering octave band average values of $\Delta L_{5.5\,\mathrm{m\,-\,ref}}$ good agreement was found between the BEM model and the full scale measurements for both the seated and standing

Table D.2: Absorption coefficients and corresponding impedance values applied to music stands.

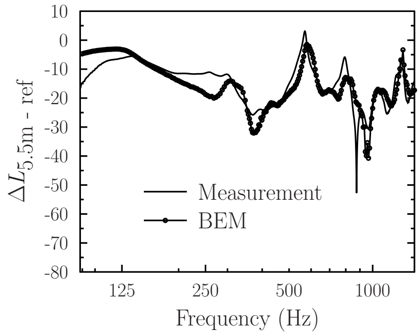
Octave (Hz)	125	250	500	1000	2000
α	0.28	0.22	0.17	0.09	0.10
$\|R\|$	0.85	0.88	0.91	0.95	0.95
Z_s (kg/m^{2}s)	5026	6639	8848	17471	15640

musician configurations. The results from the BEM model between 125–1000 Hz octave bands are within generally ± 2 dB of the full scale measurement results. Examining the un-averaged curves of $\Delta L_{5.5\,\mathrm{m}\,\text{-}\,\mathrm{ref}}$ versus frequency demonstrates that the BEM model also captures most of the smaller changes with frequency observed in the curves from the full scale measurements, see Figure D.2. The results in Figure D.2 are for a source height of 0.8 m for the seated musician case, and a source height of 1.2 m for the standing musician case. A source height of 1.0 m for the seated musician case, and source height of 1.5 m for the standing musician case were also examined with similar agreement observed.

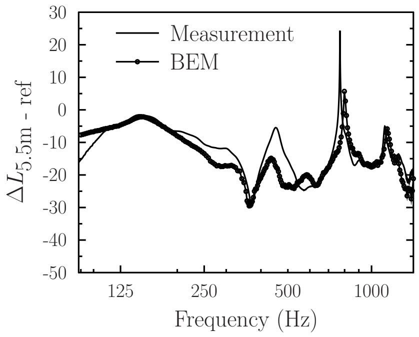
A sensitivity analysis was conducted for the impedance values of the fully validated chamber orchestra model used in this work. Increasing or decreasing the absorption coefficient by 0.1 from those used in Table D.1 (subject to the constraint that $\alpha \geq 0$) resulted in negligible change in $\Delta L_{5.5\,\mathrm{m}\,\text{-}\,\mathrm{ref}}$ across the full frequency range (125–1000 Hz octave bands), which indicated insensitivity to the exact choice of absorption applied to the musicians, as shown in Figure D.2 c. In cases where absorption coefficient could not be reduced by 0.1 (for example 125 Hz octave band) the perfectly reflective case was examined. The insensitivity to absorption coefficient suggests that the variation in $\Delta L_{5.5\,\mathrm{m}\,\text{-}\,\mathrm{ref}}$ is predominantly due to wave diffraction around the orchestra. This is unsurprising given that the wavelengths investigated (240 mm to 1.9 m) range from typical small scale feature dimension of the geometry to typical spacings between musicians.

This validation study found that good agreement was achieved between the BEM model and full scale results with both sitting and standing subjects. Based on this agreement it can be concluded that at and below the 1 kHz octave band the simplified musician geometries are satisfactory; clearly the presence of large geometries impacts the sound field over this frequency range, while the finer details do not. Throughout the validation process it was found that diffraction is dominant and results are generally insensitive to α. Based on these findings instrument geometries will be included in the final orchestra model, but applied with same impedance as the musicians.

(a)



(b)



(c)

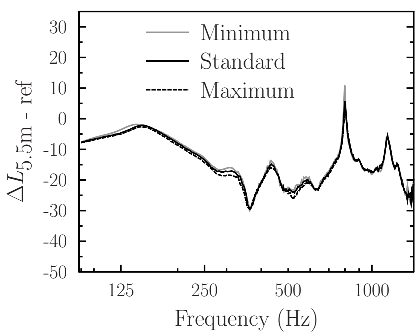


Figure D.2: Comparison of un-averaged $\Delta L_{5.5\,\mathrm{m}\text{ - ref}}$ for full scale measurements and BEM model using configuration shown in Figure D.1, for (a) standing musicians and (b) seated musicians. Additionally in (c) effect on $\Delta L_{5.5\,\mathrm{m}\text{ - ref}}$ from increasing and decreasing absorption coefficient by 0.1 for BEM model of seated musicians arranged in configuration shown in Figure D.1. Minimum refers to the lowest absorption coefficient tried, maximum refers to the highest absorption coefficient tried and standard refers to the absorption coefficients provided in Table D.1, and used in all later investigations.

Appendix E

Full scale chamber orchestra measurements: truncation of measurements to isolate early reflections

In this appendix the choice of truncation times for measurements in Hobart Town Hall with a chamber orchestra are discussed. The truncation times are selected to allow full scale measurements in situ in the hall to be compare to BEM model results. The results in this appendix are an extension to the discussion in Section 4.3.

Before investigating $\mathrm{SWC}_{\text{occ. - empty}}$ (Equation 4.3) the impulse responses were truncated. Due to limitations in signal processing, it is impossible to isolate individual reflections without smearing from adjacent reflections, unless there is an appropriate gap where no sound energy in theory arrives, as discussed by Wenmaekers et al. [2012]. Due to the size of the Hobart Town Hall, and the ornate features potentially causing scattering and diffusion, complete isolation of individual reflections is not possible; however, for comparison to the quantity $\mathrm{SWC}_{\text{occ. - empty, excl. ceiling}}$ from the BEM model, a cutoff time of 23 ms was selected to isolate reasonably well the direct sound, the back wall, left wall and right wall reflections (prior to the occurrence of the ceiling reflection). To investigate the sensitivity to the cutoff time selected, the quantity $\mathrm{SWC}_{\text{occ. - empty}}$ was plotted as a function of cutoff time for each case (Figure 4.10, Chapter 4). In particular, for values in a ± 3 ms range around the 23 ms (i.e. 20–26 ms) the change in $\text{SWC}_{\text{occ. - empty}}$ was minimal (the largest variations seen over the ±3 ms window were ±0.5 dB for Case 1, ±1.1 dB for Case 2 and ±0.2 dB for Case 3 across 125–1000 Hz octave bands). The ±1.1 dB variation for Case 2 was in the 1000 Hz octave band, and can be observed in Figure 4.10b where $\text{SWC}_{\text{occ. - empty}}$ is changing between 20–26 ms.

To compare to the quantity $\text{SWC}_{\text{occ. - empty, incl. ceiling}}$, the signal was truncated at 40 ms for Cases 1 and 2, and at 43 ms for Case 3, based on the arrival time of the ceiling (and ceiling/floor) reflection in each case, see Figure 4.5. The truncation times were selected to include the second-order ceiling/floor reflection because the floor reflection occurring after each first-order enclosure reflection was inherent in the BEM model due to symmetry. This unavoidably included other second-order reflections which are not included in the BEM model. Again, $\text{SWC}_{\text{occ. - empty}}$ values in a ±3 ms range around the 40 ms (37–43 ms) were investigated for Cases 1 and 2, and around the 43 ms (40–46 ms) for Case 3. The changes in $\text{SWC}_{\text{occ. - empty}}$ over the ±3 ms windows were minimal (largest variations seen over the ±3 ms window were ±0.6 dB for Case 1, ±0.3 dB for Case 2 and ±0.2 dB for Case 3 across 125–1000 Hz octave bands).

Appendix F

Background to Higher Order Ambisonics

The on-stage acoustic measurements in this study were completed using a 32-channel spherical microphone array. This opens up the potential to analyse the directionality of on-stage sound fields using 4^{th} order Ambisonics (or lower). In this appendix the background for this type of analysis is summarised.

Any arbitrary spatial directionality function s(θ,ϕ) can be represented as a weighted sum of any infinite set of orthogonal basis functions

$$s(\theta, \phi) = \sum_{j=1}^{\infty} w_j c_j(\theta, \phi) \tag{F.1}$$

where $c_j(\theta, \phi)$ are the basis functions (in the higher order Ambisonic form these are the spherical harmonics $Y_n^m(\theta, \phi)$ [Rafaely, 2015]) and w_j are the weights.

The spherical harmonics can be defined as

$$Y_n^m(\theta, \phi) = \sqrt{\frac{2n+1}{4\pi} \frac{(n-m)!}{(n+m)!}}) P_n^m(\cos\theta) e^{im\phi} \tag{F.2}$$

where (.)! represented the factorial function, $P_n^m(.)$ are the Associated Legendre Functions, m is an integer denoting function degree and n is a natural number denoting function order

[Abramowitz and Stegun, 1964].

We multiply by $c_i(\theta,\phi)$, integrate over the unit sphere and use the orthogonality condition $\sum_{j=0}^{\infty}\oint c_j(\theta,\phi)c_i(\theta,\phi)\,dA = 0$ for $i \neq j$ to obtain the spherical Fourier transform

$$\begin{aligned}\oint c_i(\theta,\phi)s(\theta,\phi)\,dA &= \sum_{j=1}^{\infty}\oint w_j c_j(\theta,\phi)c_i(\theta,\phi)\,dA \\ &= w_i \oint c_i^2(\theta,\phi)\,dA, \end{aligned} \tag{F.3}$$

which yields the weights w_i of harmonic component i by rearrangement. In this implementation the functions $Y_n^m(\theta,\phi)$ are normalised such that the area-averaged of its square value is 1, hence the last integral is 4π, the area of the unit sphere.

In this work, we have two tasks: to convert the 32 microphone signals into spherical harmonic channels (thereby encoding the measurements in a general and hardware-independent format); and to find the optimum combination of these channels to capture and reject sound respectively originating from a desired solid angle and its complement. The two are closely related problems solved very similarly, though the former must account for the scattering of the incident waves by the rigid sphere that approximates the microphone, and was already implemented in AARAE [Cabrera et al., 2014].

In discrete form, if we define the surface of the sphere by a large number N points each representing as nearly as possible equal area, the integrals above may be approximated as sums, hence Equation F.3 becomes

$$w_i = \frac{\sum_{k=1}^{N} c_{k,i}s_k}{\sum_{k=1}^{N} c_{k,i}^2} = \frac{1}{N}\sum_{k=1}^{N} c_{k,i}s_k \tag{F.4}$$

where $c_{k,i}$ and s_k are respectively $c_i(\theta,\phi)$ and $s(\theta,\phi)$ evaluated at the k^{th} point with coordinates θ_k,ϕ_k, and again the denominator has been simplified to N by the normalisation of $c_i(\theta,\phi)$. If we truncate the infinite series to represent the function s_k with finite order Ambisonic components (hence a finite number of basis functions and weights) then this can be expressed in matrix form as

$$\{w\} = \frac{1}{N}[c]^T\{s\} \tag{F.5}$$

where columns of $[c]$ represent each basis function evaluated at all points.

We note that an alternative form based on the second integral of Equation F.3 is $\{w\} = ([c]^T[c])^{-1}[c]^T\{s\}$, (where $[c]^T[c] = N[I]$ due to the orthogonality and normalization of $c_i(\theta,\phi)$). If $\{s\}$ is longer than $\{w\}$ this is simply the least squares solution to the over-specified problem $\{s\} = [c]\{w\}$. Thus in intuitive terms the weights are those that provide the best fit of the spherical harmonics of a given order to the desired spatial directionality function.

Finally, in order to capture or reject sound in a given region we define $s_k = 1$ or 0 respectively. The spatial analysis implemented in AARAE provides the spherical harmonic functions at 3002 nearly equally spaced points on the sphere, and thus the spatial filters also contain points (with values zero or one) at 3002 nearly evenly spaced points on the sphere.

Appendix G

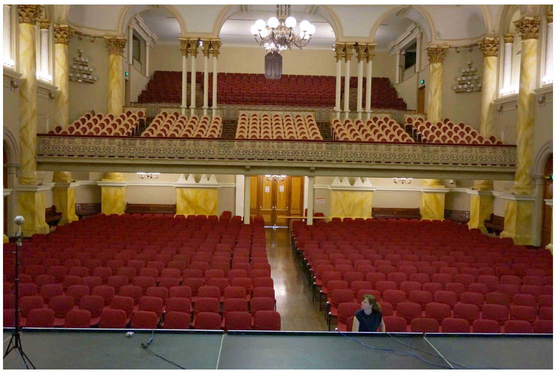
Auditorium photographs

Additional images of the auditoria measured are presented here, including stage and auditorium photographs.

(a) PH stage

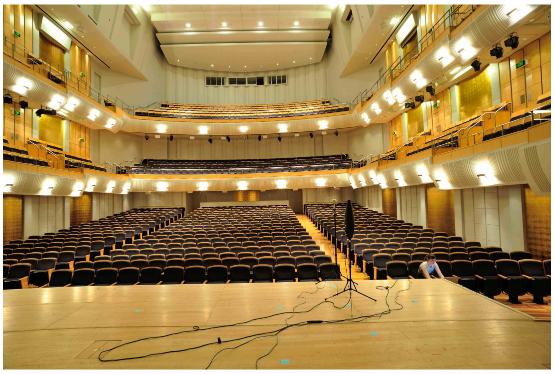
(b) PH audience

(c) AH stage



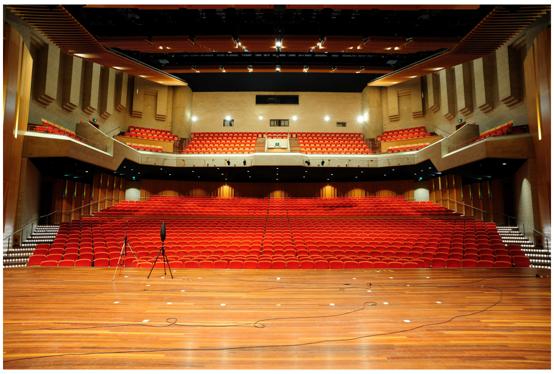
(d) AH audience

(e) AP stage



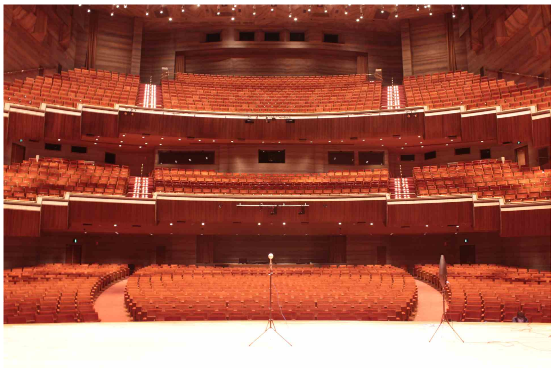
(f) AP audience

(g) LH stage

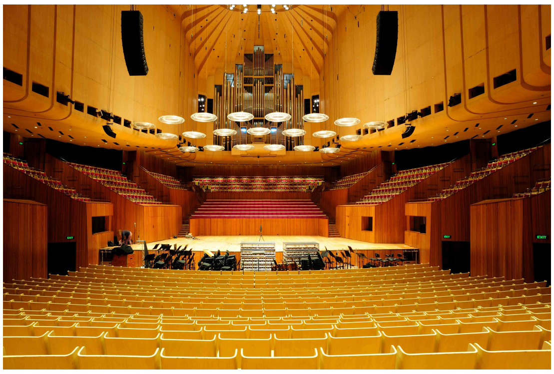


(h) LH audience

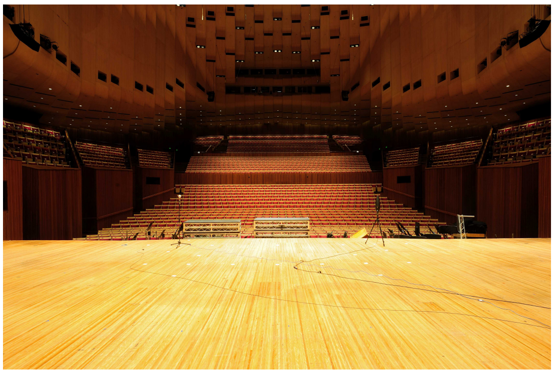
(i) HH stage



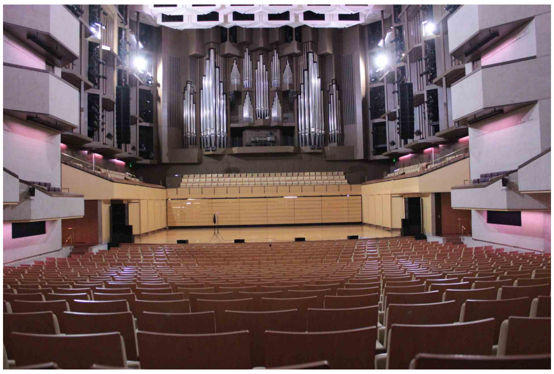
(j) HH audience



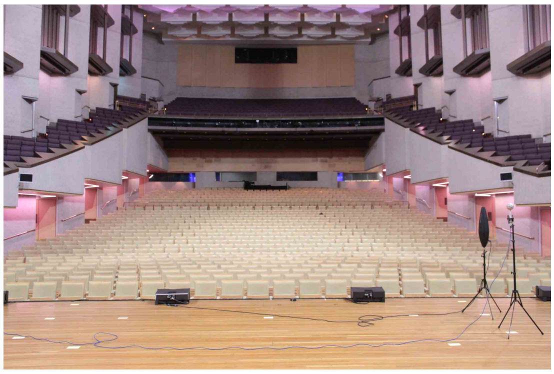
(k) SO stage



(l) SO audience



(m) QC stage



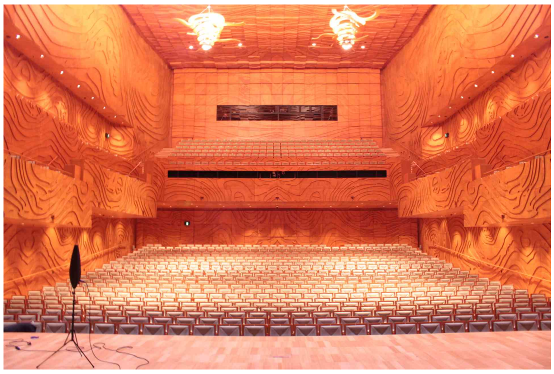
(n) QC audience

(o) WH stage

(p) WH audience

Figure G.1: Addtional images of auditoria assessed by ACO.

(a) MC stage



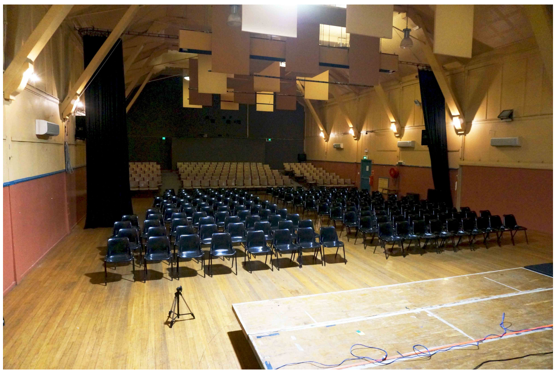
(b) MC audience

(c) HT stage

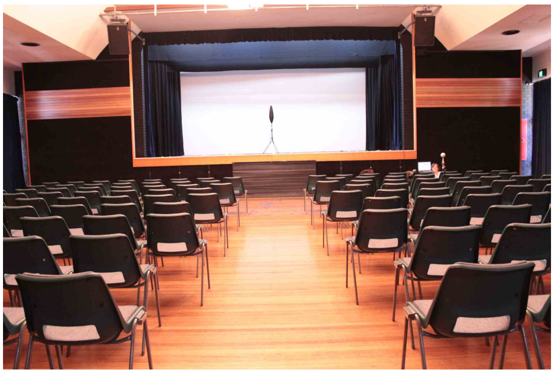
(d) HT audience

Figure G.2: Addtional images of auditoria assessed by chamber ensembles.

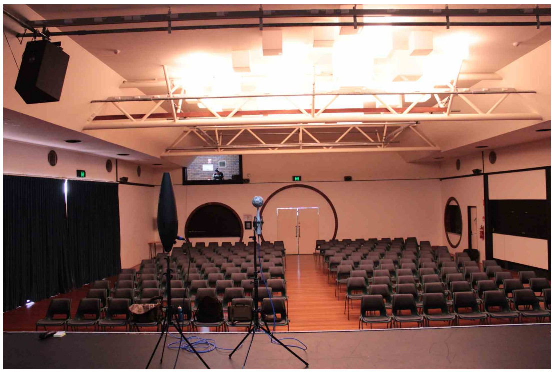
(a) BEL stage



(b) BEL audience



(c) CLE stage



(d) CLE audience

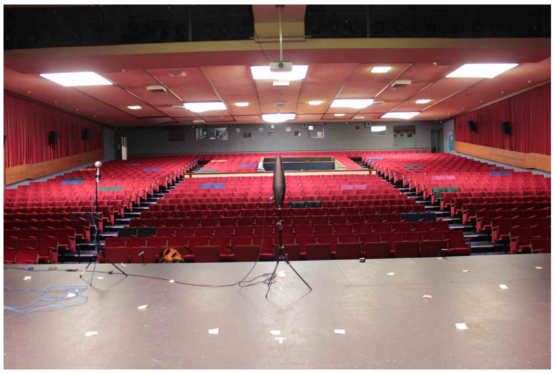
(e) MUL stage

(f) MUL audience

(g) ARM stage

(h) ARM audience

(i) BUN stage



(j) BUN audience

Figure G.3: Addtional images of auditoria assessed by ACO2.

Appendix H

Stage diagrams

In this appendix stage diagrams are provided for those stages on which acoustic measurements were conducted. If a stage diagram was available in the technical specifications of the auditoria this has been provided, where this wasn't available a stage diagram with the main dimensions have been draw. Dimensions are given in metres, unless otherwise specified.

H.1 Purpose-built auditoria

Stage diagrams for purpose-built auditoria are included in this section. The auditoria considered to be purpose-built in this study are Perth Concert Hall (PH), Adelaide Town Hall (AH), Sydney City Recital Hall Angel Place (AP), Llewellyn Hall Canberra (LH), Hamer Hall Melbourne (HH), Sydney Opera House Concert Hall (SO), QPAC Queensland Performing Arts Centre Brisbane (QC), Wollongong Town Hall (WH), Melbourne Recital Centre (MC) and Hobart Town Hall (HT).

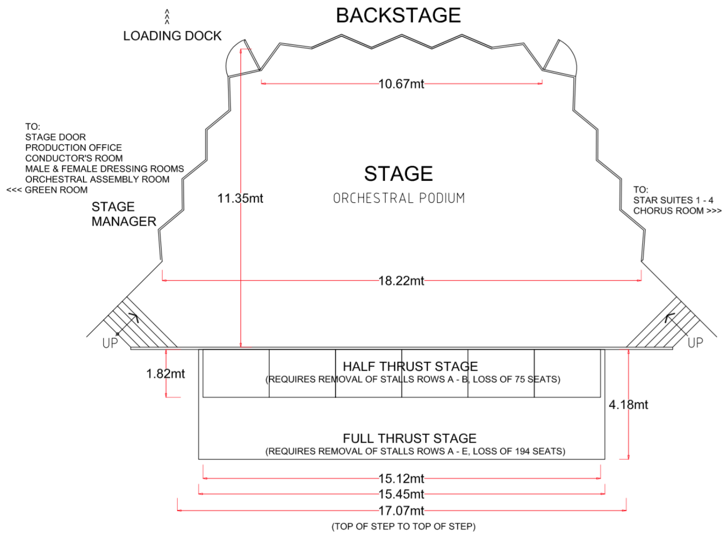


Figure H.1: Stage diagram for Perth Concert Hall (PH). The stage extension is shown, but was not used in measurements. Image courtesy of Perth Concert Hall [2015].

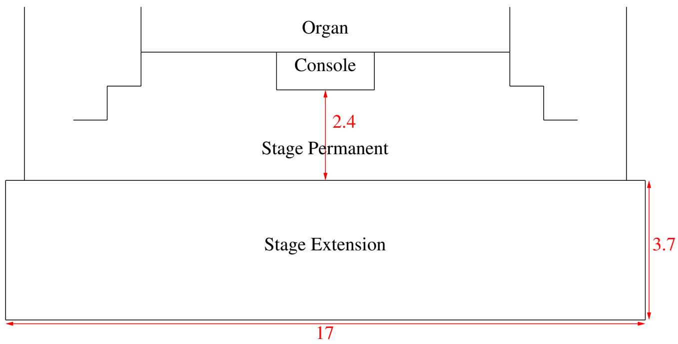


Figure H.2: Stage diagram for Adelaide Town Hall (AH), with the 3.7 m stage extension in place (as used during stage measurements).

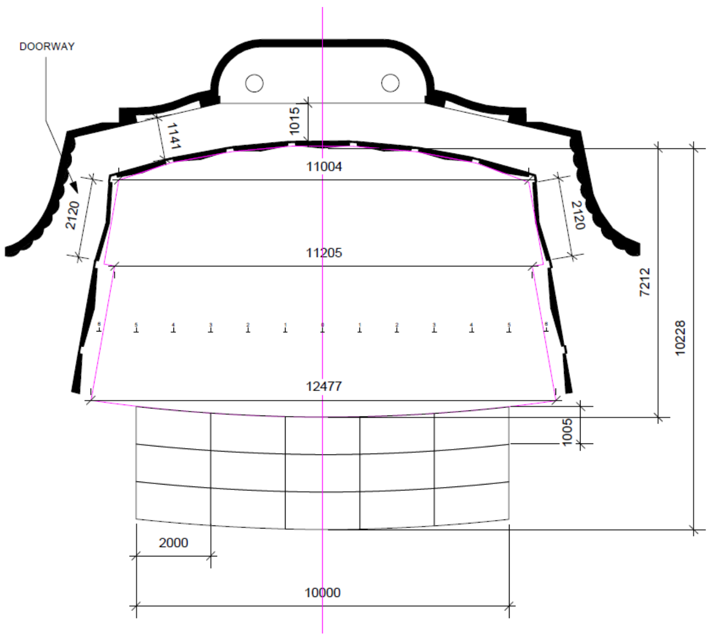


Figure H.3: Stage diagram for City Recital Centre, Angel Place in Sydney (AP) with 1, 2 and 3 m stage extension shown. Measurements were conducted with no stage extension and with 2 m stage extension. Image courtesy of City Recital Centre, Angel Place [2016]. Dimensions in millimetres.

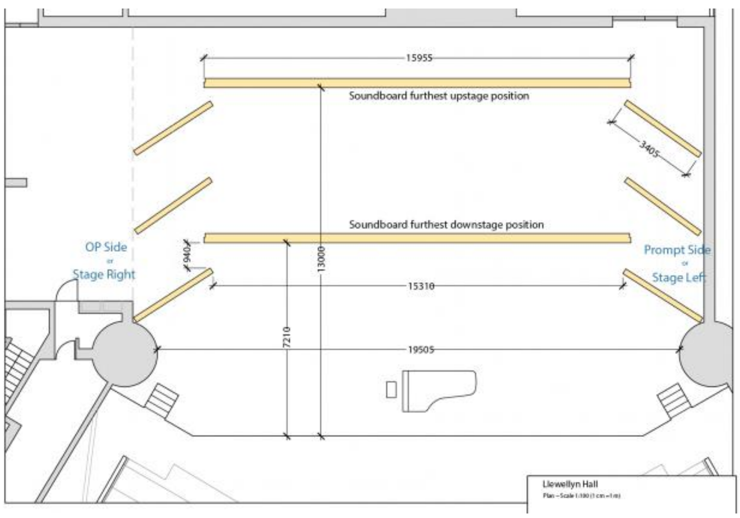


Figure H.4: Stage diagram for Llewellyn Hall in Canberra (LH). Backwall was positioned 8 m from front of stage for measurements. Image courtesy of Llewellyn Concert Hall [2017]. Dimensions in millimetres.

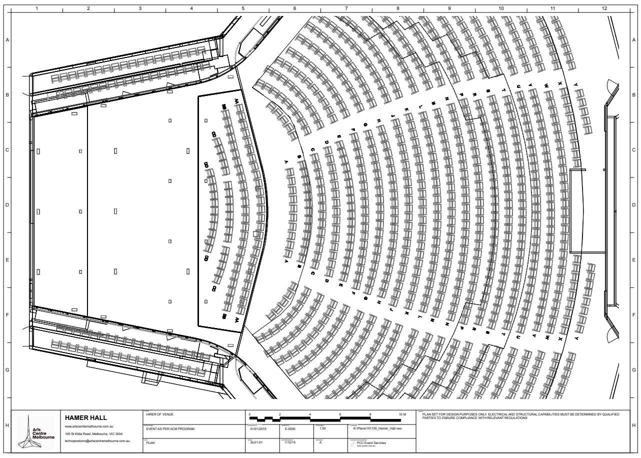


Figure H.5: Stage diagram for Hamer Hall in Melbourne (HH). Image courtesy of Hamer Hall [2016].

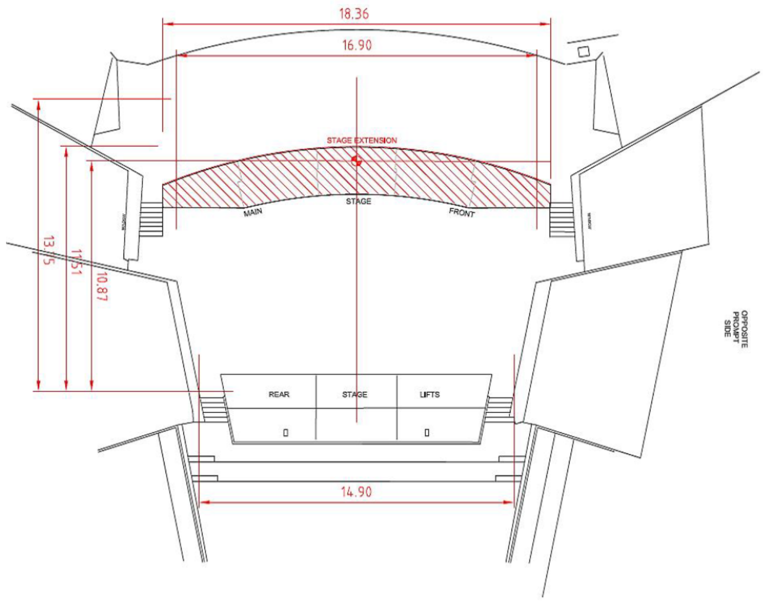


Figure H.6: Stage diagram for Sydney Opera House (SO). The stage extension is shown, but was not used in measurements. Image courtesy of Sydney Opera House [2016].

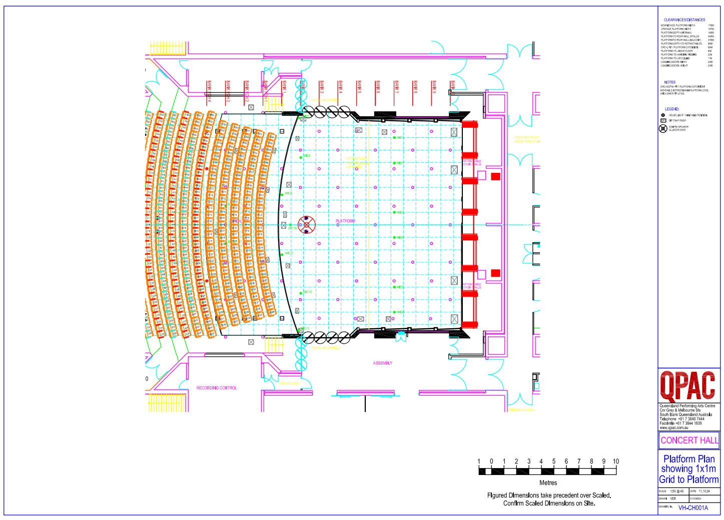


Figure H.7: Stage diagram for Queensland Performing Arts Centre Concert Hall (QC). Image courtesy of Queensland Performing Arts Centre [2016].

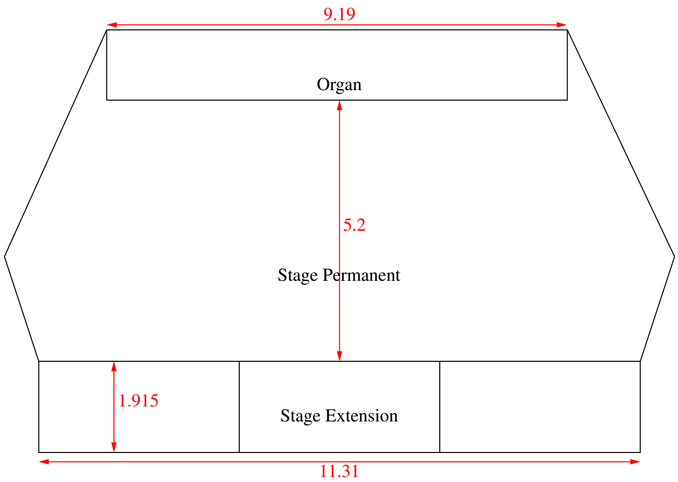


Figure H.8: Stage diagram for Wollongong Town Hall (WH). The stage extension is in three parts, as shown, and was used during measurements.

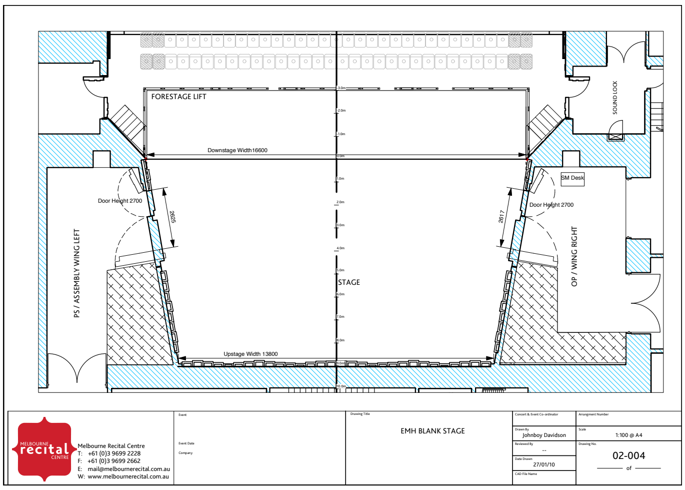


Figure H.9: Stage diagram for Elisabeth Murdoch Hall, Melbourne Recital Centre (MR). Image courtesy of Melbourne Recital Centre [2010]. Dimensions in millimetres.

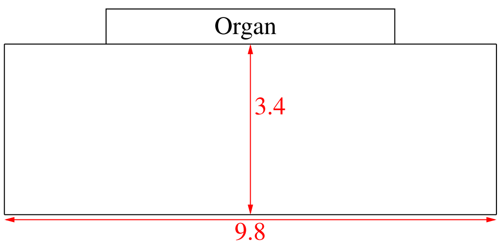


Figure H.10: Stage diagram for Hobart Town Hall (HT).

H.2 Regional auditoria

Stage diagrams for regional auditoria are included in this section. The auditoria considered to be regional in this study are Bellingen Memorial Hall (BEL), the Auditorium at Redland Performing Arts Centre, Cleveland (CLE), St John's School Hall, Mullumbimby (MUL), Armidale Town Hall (ARM) and Moncrieff Theatre, Bundaberg (BUN).

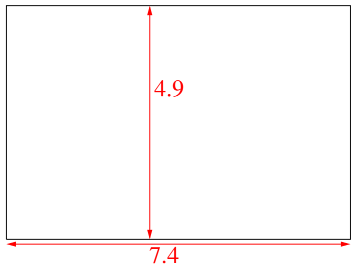


Figure H.11: Stage diagram for Bellingen Memorial Hall (BEL). Note: stage diagram is a for make-shift stage used by ACO2.

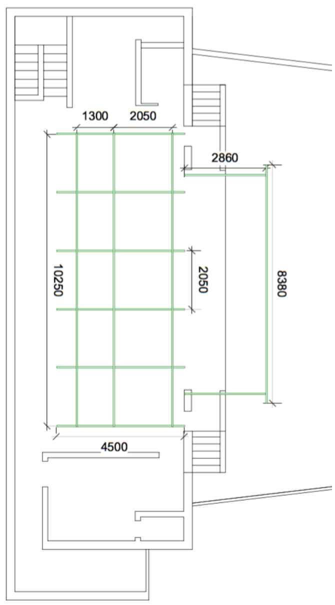


Figure H.12: Stage diagram for Auditorium at Redland Performing Arts Centre, Cleveland (CLE). Image courtesy of Redland Performing Arts Centre. Dimensions in millimetres.

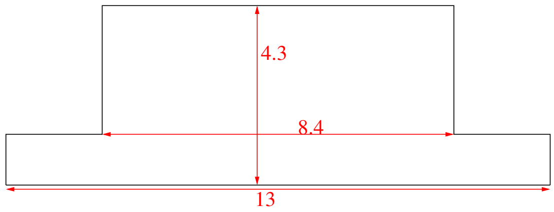


Figure H.13: Stage diagram for St John's School Hall, Mullumbimby (MUL).

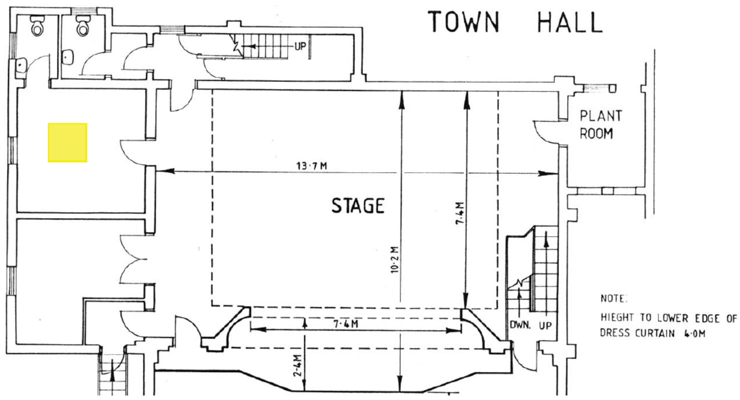


Figure H.14: Stage diagram for Armidale Town Hall (ARM). Image courtesy of Armidale Town Hall [2016].

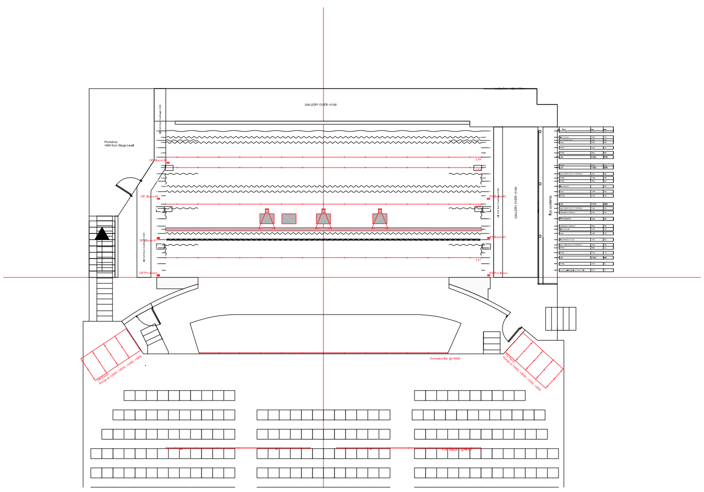


Figure H.15: Stage diagram for Moncrieff Theatre, Bundaberg (BUN). Image courtesy of Moncrieff Theatre [2016].

Appendix I

Effect of microphone on omnidirectional parameters

The use of the Eigenmike to derive omnidirectional parameters was validated by comparing ST_{early}, ST_{late}, T_{30} and G, as measured with the Eigenmike and with the Brüel&Kjær omnidirectional receiver type 4190. The comparison was made between measurements conducted using both in four auditoria using the same measurement procedure and source (Brüel&Kjær omnidirectional loudspeaker type 4295).

In Table I.1 the support measures (ST_{early} and ST_{late}) are presented for source positions S1 and S2 (S1 and S2 are defined in Figure 5.7, Chapter 5). These results are the arithmetic average of the values in decibels from four measurements taken at a 1 m radius around each source position, and again averaged arithmetically over the 250–2000 Hz octave bands. The position average is used because support parameters are commonly expressed as an arthimetic average of 1 m measurements at several locations on stage [ISO-3382-1, 2009]. The difference between the ST measures determined by the Eigenmike and the B&K omnidirectional microphone is at worst 0.5 dB and generally within ±0.3 dB.

T_{30} derived from a 6 m source-receiver distance across stage (from S1 to S4) was investigated for octave bands 125–4000 Hz. The maximum deviation between the two microphones was 0.08 s. Such a small deviation is expected as the microphone type should not impact a reverberation parameter. This observed difference is also significantly less than differences that can be caused by the underlying calculation method used to calculate T_{30} [Cabrera et al., 2016].

Additionally, differences between microphones for the sound strength parameter G on stage were investigated. This is a more stringent test since it involves absolute rather than relative levels. For this analysis the Brüel&Kjær omnidirectional loudspeaker was calibrated in an anechoic chamber using the Brüel&Kjær omnidirectional microphone, according to ISO-3382-1 [2009], see Appendix K. Measurements in the anechoic chamber with the Eigenmike and omnidirectional microphone allowed a 'transfer function' between the Eigenmike and omnidirectional microphone to be produced, used to adjust the Eigenmike G values before comparing. The across-stage measurements (source-receiver distance between 2.7 m and 6 m) and octave bands 125–4000 Hz were investigated. In this case across-stage measurements were used and so position averaging was not conducted. To give an example of differences for G, in Table I.2 results are presented for the source at position S1 and the receiver at position S2. These results are typical, and differences for G for all other source-receiver combinations were also examined. The deviations for G from each microphone were mostly less than 1 dB, with the absolute worst deviation for any source-receiver distance being 1.7 dB.

Table I.1: Difference between ST measures with Eigenmike and omnidirectional microphone

			250-2000 Hz Average (arithmetic)			
	Parameter	Microphone	AP	LH	SO	WH
Pos S1	ST_{early}	Omni	-11.64	-13.43	-15.07	-5.84
		Eigen	-11.33	-13.80	-15.41	-6.32
		Diff (Omni - Eigen)	**-0.31**	**0.37**	**0.31**	**0.48**
	ST_{late}	Omni	-12.05	-13.51	-13.80	-6.42
		Eigen	-11.74	-13.81	-13.80	-6.68
		Diff(Omni-Eigen)	**-0.32**	**0.30**	**0.00**	**0.26**
Pos S2	ST_{early}	Omni	-13.57	-13.73	-15.11	-7.36
		Eigen	-13.78	-14.30	-15.40	-7.61
		Diff (Omni - Eigen)	**0.21**	**0.57**	**0.29**	**0.25**
	ST_{late}	Omni	-13.78	-13.95	-15.18	-10.53
		Eigen	-13.91	-14.31	-15.12	-10.60
		Diff(Omni-Eigen)	**0.13**	**0.36**	**-0.04**	**0.07**

Table I.2: Difference between G with Eigenmike and omnidirectional microphone for source at position S1 and receiver at position S2.

Octave (Hz)	Microphone	AP	LH	SO	WH
125	Omni	12.0	10.6	8.8	14.2
	Eigen	12.1	8.4	8.4	13.5
	Diff (Omni - Eigen)	**0.1**	**-0.7**	**-0.5**	**-0.8**
250	Omni	15.7	16.5	15.3	19.5
	Eigen	16.0	16.0	15.6	18.8
	Diff (Omni - Eigen)	**0.3**	**-0.4**	**-0.3**	**0.7**
500	Omni	12.8	12.3	12.0	17.2
	Eigen	14.2	12.7	12.7	16.9
	Diff (Omni - Eigen)	**1.4**	**0.4**	**0.8**	**-0.3**
1000	Omni	15.1	14.3	14.4	18.5
	Eigen	15.3	14.3	14.0	17.6
	Diff (Omni - Eigen)	**0.3**	**0.0**	**0.3**	**-0.9**
2000	Omni	14.4	14.3	13.7	18.9
	Eigen	14.8	13.4	13.3	18.2
	Diff (Omni - Eigen)	**0.4**	**-0.8**	**0.4**	**-0.6**
4000	Omni	13.8	13.4	12.8	15.8
	Eigen	15.4	13.7	13.7	14.9
	Diff (Omni - Eigen)	**1.7**	**0.3**	**0.9**	**-0.8**

Appendix J

Stage Parameters

J.1 Purpose-built auditoria

Tabulated values for stage parameters in purpose-built auditoria are included in this section. The auditoria considered to be purpose-built in this study are Perth Concert Hall (PH), Adelaide Town Hall (AH), Sydney City Recital Hall Angel Place (AP), Llewellyn Hall Canberra (LH), Hamer Hall Melbourne (HH), Sydney Opera House Concert Hall (SO), QPAC Queensland Performing Arts Centre Brisbane (QC), Wollongong Town Hall (WH), Melbourne Recital Centre (MC) and Hobart Town Hall (HT).

J.1.1 Omnidirectonal Parameters

J.1.1.1 Results for ST_{early} on stage

Table J.1: ST_{early} for 1 m measurements at position S1 (arthimetic average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	−15.4	−13.6	−10.8	−13.4	−13.7	−18.3	−17.5	−12.5	−9.5
500	−15.1	−13.3	−11.7	−15.9	−15.2	−17.3	−16.2	−8.7	−12.0
1000	−14.1	−13.0	−11.3	−12.7	−14.0	−16.5	−14.4	−8.4	−11.6
2000	−14.7	−13.2	−11.5	−13.2	−14.7	−17.3	−15.4	−9.2	−11.2

Table J.2: ST_{early} for 1 m measurements at position S2 (arthimetic average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC	HT
250	−14.2	−13.8	−12.3	−13.7	−11.7	−13.0	−14.1	−7.0	−9.0	−9.3
500	−16.0	−11.5	−11.9	−14.9	−14.6	−14.3	−17.3	−6.0	−10.4	−8.2
1000	−14.2	−11.4	−10.4	−13.2	−11.9	−13.1	−13.3	−6.8	−10.0	−7.1
2000	−14.6	−12.2	−11.1	−13.5	−13.6	−14.8	−14.4	−7.1	−10.5	−6.4

Table J.3: ST_{early} for 1 m measurements at position S3 (arthimetic average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC	HT
250	−14.5	−13.0	−12.2	−13.7	−10.9	−12.9	−14.5	−6.1	−9.4	−8.7
500	−15.4	−11.7	−11.4	−14.9	−14.2	−13.9	−17.0	−6.5	−10.1	−8.7
1000	−13.8	−11.2	−10.5	−13.0	−12.2	−13.8	−12.4	−5.3	−10.0	−8.1
2000	−14.9	−10.4	−11.0	−13.7	−13.5	−13.9	−14.5	−6.3	−10.4	−7.9

Table J.4: ST_{early} for 1 m measurements at position S4 (arthimetic average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	−14.9	−12.4	−12.4	−12.8	−13.8	−12.7	−17.4	−5.4	−10.1
500	−14.9	−12.5	−12.3	−16.2	−15.9	−14.5	−16.6	−6.3	−11.7
1000	−13.2	−11.8	−11.5	−13.2	−14.3	−14.8	−14.6	−5.2	−11.7
2000	−13.6	−11.8	−12.6	−13.1	−14.7	−15.5	−15.0	−6.1	−10.8

J.1.1.2 Results for ST_{late} on stage

Table J.5: ST_{late} for 1 m measurements at position S1 (arthimetic average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	−14.1	−12.5	−13.9	−14.3	−15.5	−16.2	−15.7	−10.4	−11.3
500	−14.1	−11.7	−13.7	−14.5	−15.2	−15.2	−14.7	−6.9	−12.9
1000	−12.9	−11.5	−13.6	−14.1	−15.3	−14.3	−13.3	−6.0	−12.4
2000	−13.4	−12.7	−13.3	−14.4	−16.5	−14.9	−13.6	−6.9	−12.8

Table J.6: ST_{late} for 1 m measurements at position S2 (arthimetic average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC	HT
250	−14.7	−12.5	−12.7	−13.6	−15.5	−16.7	−14.9	−12.2	−11.7	−8.6
500	−13.6	−11.6	−13.7	−14.7	−15.3	−15.2	−13.5	−9.8	−12.9	−8.4
1000	−12.6	−11.1	−13.3	−13.9	−15.7	−14.7	−12.3	−9.7	−12.6	−8.6
2000	−13.4	−12.3	−13.2	−14.2	−16.3	−15.0	−13.3	−10.8	−13.4	−9.7

Table J.7: ST_{late} for 1 m measurements at position S3 (arthimetic average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC	HT
250	−14.6	−12.3	−12.6	−13.7	−14.8	−16.5	−13.9	−11.4	−11.8	−8.9
500	−13.6	−11.7	−14.0	−14.4	−15.5	−15.4	−13.3	−9.9	−12.7	−8.5
1000	−12.9	−11.1	−13.4	−13.7	−15.2	−14.5	−12.5	−9.4	−12.5	−8.5
2000	−13.4	−11.9	−13.1	−14.3	−16.3	−14.7	−12.0	−10.8	−13.0	−9.8

Table J.8: ST_{late} for 1 m measurements at position S4 (arthimetic average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	−13.7	−12.5	−14.1	−13.8	−15.5	−15.9	−16.0	−9.9	−11.6
500	−14.0	−11.6	−14.1	−14.4	−15.2	−15.0	−14.4	−6.7	−13.1
1000	−12.9	−11.4	−13.5	−13.7	−15.7	−14.3	−13.3	−5.5	−12.7
2000	−13.3	−12.5	−13.5	−13.9	−16.5	−14.3	−13.4	−6.9	−12.7

J.1.1.3 Results for G_e on stage with various source-receiver distances

Table J.9: G_e for 2.7 m source-receiver measurements (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	15.7	12.7	15.9	15.5	15.1	15.5	14.6	17.2	15.7
500	11.7	9.9	12.8	11.7	11.8	12.1	11.8	15.1	11.7
1000	13.6	11.3	14.7	13.5	13.8	13.4	13.1	16.3	13.6
2000	12.6	10.8	13.9	12.4	12.8	13.3	13.0	16.7	12.6

Table J.10: G_e for 4 m source-receiver measurements (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	10.4	8.3	12.5	9.7	10.5	11.9	13.6	13.9	10.4
500	10.5	10.0	12.0	10.8	10.7	10.5	11.4	12.6	10.5
1000	11.1	9.5	12.7	11.7	11.8	11.1	12.6	15.1	11.1
2000	10.0	8.9	12.2	9.8	10.6	10.8	11.8	14.7	10.0

Table J.11: G_e for 5.6 m source-receiver measurements (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	4.3	4.3	9.6	7.7	6.8	9.3	4.0	12.8	4.3
500	9.1	6.8	10.2	8.1	8.5	9.6	8.5	13.6	9.1
1000	7.5	6.1	9.5	7.4	7.1	7.7	7.2	14.6	7.5
2000	9.2	7.9	11.7	8.5	8.8	11.0	9.8	15.7	9.2

Table J.12: G_e for 6 m source-receiver measurements (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	8.0	4.0	9.6	9.5	9.4	10.1	5.7	12.0	8.0
500	9.6	6.3	10.9	9.8	9.5	9.6	9.4	13.6	9.6
1000	8.1	6.0	11.1	8.2	8.0	7.2	8.6	12.6	8.1
2000	7.5	5.3	9.5	7.7	8.3	8.1	7.1	13.8	7.5

J.1.1.4 Results for G_l on stage with various source-receiver distances

Table J.13: G_l for 2.7 m source-receiver measurements (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	5.8	8.2	8.4	6.9	5.7	5.2	4.7	10.9	9.3
500	6.7	7.8	7.5	5.0	5.3	5.9	5.8	11.8	7.8
1000	6.6	8.6	6.9	5.7	4.7	6.0	6.0	12.2	7.7
2000	7.0	8.2	7.3	6.0	5.3	6.4	7.7	11.3	8.2

Table J.14: G_l for 4 m source-receiver measurements (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	6.8	7.7	7.0	8.4	7.0	3.6	7.8	10.3	9.5
500	7.8	9.4	6.2	6.5	5.8	5.1	7.7	11.3	9.0
1000	8.3	8.9	6.6	6.9	5.4	5.9	7.8	9.8	8.1
2000	7.7	8.7	7.0	6.7	6.1	6.9	7.9	9.8	7.9

Table J.15: G_l for 5.6 m source-receiver measurements (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	4.3	7.3	8.0	5.1	3.5	5.9	5.2	10.1	9.9
500	5.3	7.5	7.4	4.3	3.7	6.2	6.0	11.2	8.6
1000	6.0	8.0	7.1	5.1	3.6	6.2	6.0	11.4	8.2
2000	6.4	7.6	7.8	5.5	3.9	6.4	6.3	10.6	8.5

Table J.16: G_l for 6 m source-receiver measurements (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	8.1	8.7	6.6	8.0	7.8	3.9	7.0	10.5	8.6
500	7.7	8.8	5.9	6.5	7.2	4.9	7.6	13.0	7.2
1000	7.3	8.4	6.3	5.9	5.1	5.4	7.3	14.8	7.2
2000	7.3	7.7	7.1	6.0	5.3	6.6	7.7	13.4	8.4

J.1.2 Spatial Parameters

J.1.2.1 Results for TS_{20-50} on stage

Table J.17: TS_{20-50} for 1 m measurements at position S1 (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	−7.0	−6.6	−6.1	−6.6	−3.8	−3.1	−7.2	−1.8	−7.0
500	−5.7	−7.9	−5.8	0.8	0.7	−3.8	−7.1	0.7	−2.7
1000	−8.4	−9.7	−11.2	−4.4	−5.2	−2.4	−12.5	0.4	−7.6
2000	−10.9	−8.7	−13.2	−3.4	−2.8	−5.7	−13.6	−0.6	−10.2

Table J.18: TS_{20-50} for 1 m measurements at position S2 (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC	HT
250	−8.2	−4.4	−6.3	−4.7	−5.1	−5.9	−8.6	−1.8	−4.8	−2.9
500	−5.5	−6.4	−5.7	3.0	2.4	−0.3	−9.1	−0.5	−1.2	−1.4
1000	−7.2	−9.2	−11.9	1.9	−4.8	−4.8	−17.0	0.5	−5.2	−5.4
2000	−8.5	−8.7	−10.0	1.3	−1.4	−3.9	−13.7	−3.0	−8.9	−6.9

Table J.19: TS_{20-50} for 1 m measurements at position S3 (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC	HT
250	−7.5	−5.2	−6.8	−3.9	−6.3	−5.7	−7.7	−2.9	−6.5	−2.8
500	−5.8	−5.8	−5.3	2.6	3.1	−3.5	−8.4	0.2	−1.4	−0.8
1000	−8.0	−8.0	−13.3	−1.5	−4.3	−4.3	−18.2	−0.9	−6.3	−4.2
2000	−7.7	−7.0	−11.5	−0.9	−4.8	−5.8	−14.1	−1.8	−8.6	−4.8

Table J.20: TS_{20-50} for 1 m measurements at position S4 (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	−5.4	−8.2	−7.4	−6.7	−3.4	−6.6	−7.5	−2.2	−6.2
500	−4.3	−7.0	−6.2	2.0	1.1	−2.8	−5.6	0.2	−4.3
1000	−8.6	−8.4	−11.8	−3.6	−4.4	−3.7	−12.5	1.6	−7.5
2000	−8.9	−9.1	−13.7	−3.3	−3.5	−4.2	−14.3	−1.5	−9.7

J.1.2.2 Results for TH_{20-50} on stage

Table J.21: TH_{20-50} for 1 m measurements at position S1 (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	−11.9	−14.4	−8.6	−12.1	−8.1	−6.5	−10.5	−6.7	−12.6
500	−10.8	−14.5	−8.5	−4.5	−3.4	−6.4	−9.0	−4.0	−8.2
1000	−12.7	−14.2	−11.1	−8.3	−7.2	−3.1	−13.0	−1.3	−10.2
2000	−12.0	−9.5	−12.1	−5.2	−2.9	−4.9	−12.7	−1.4	−10.7

Table J.22: TH_{20-50} for 1 m measurements at position S2 (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC	HT
250	−14.4	−10.9	−11.1	−11.5	−12.4	−11.9	−11.9	−11.9	−11.4	−8.3
500	−12.8	−14.1	−10.1	−5.4	−3.2	−6.5	−11.4	−11.4	−10.7	−7.0
1000	−15.1	−13.6	−13.6	−6.5	−10.0	−7.0	−16.6	−16.6	−9.6	−8.4
2000	−12.0	−13.1	−13.1	−1.6	−2.5	−5.4	−12.4	−12.4	−10.0	−7.0

Table J.23: TH_{20-50} for 1 m measurements at position S3 (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC	HT
250	−13.7	−11.7	−11.8	−10.6	−12.0	−11.8	−11.1	−7.7	−13.0	−7.8
500	−13.3	−13.3	−11.6	−6.0	−3.9	−8.6	−10.6	−6.5	−10.5	−7.2
1000	−15.5	−13.3	−16.8	−7.1	−7.5	−5.6	−17.6	−5.7	−10.5	−7.4
2000	−12.0	−10.4	−12.2	−3.0	−4.0	−6.0	−12.8	−3.3	−8.8	−4.9

Table J.24: TH_{20-50} for 1 m measurements at position S4 (power average) across individual octaves 250–2000 Hz.

Octave (Hz)	PH	AH	AP	LH	HH	SO	QC	WH	MC
250	−9.9	−13.7	−12.1	−12.0	−8.2	−9.5	−10.8	−7.0	−12.0
500	−8.9	−15.1	−10.3	−2.5	−3.5	−5.2	−7.6	−4.3	−10.5
1000	−11.2	−15.2	−13.6	−7.4	−7.1	−5.1	−12.5	−1.2	−11.1
2000	−10.1	−9.9	−13.2	−4.4	−4.0	−3.9	−13.3	−2.4	−10.7

J.2 Regional auditoria

Tabulated values for stage parameters in regional auditoria are included in this section. The auditoria considered to be regional in this study are Bellingen Memorial Hall (BEL), the Auditorium at Redland Performing Arts Centre, Cleveland (CLE), St John's School Hall, Mullumbimby (MUL), Armidale Town Hall (ARM) and Moncrieff Theatre, Bundaberg (BUN).

J.2.1 Results for ST_{early} on stage

Table J.25: ST_{early} for 1 m measurements at position S1 (arthimetic average) across individual octaves 250–1000 Hz.

Octave (Hz)	BEL	CLE	MUL	ARM	BUN
250	−7.0	−6.0	−7.1	−14.8	−10.2
500	−8.4	−6.9	−8.5	−15.0	−10.1
1000	−8.4	−7.6	−7.4	−14.4	−9.6

Table J.26: ST_{early} for 1 m measurements at position S2 (arthimetic average) across individual octaves 250–1000 Hz.

Octave (Hz)	BEL	CLE	MUL	ARM	BUN
250	−8.3	−6.9	−2.3	−12.5	−10.1
500	−8.6	−6.6	−5.7	−13.4	−11.5
1000	−8.6	−6.5	−6.6	−12.6	−9.6

Table J.27: ST_{early} for 1 m measurements at position S3 (arthimetic average) across individual octaves 250–1000 Hz.

Octave (Hz)	BEL	CLE	MUL	ARM	BUN
250	−8.1	−8.3	−2.9	−11.5	−9.5
500	−7.5	−7.8	6.3	−14.0	−11.1
1000	−8.6	−7.5	−6.5	−12.0	−10.0

Table J.28: ST_{early} for 1 m measurements at position S4 (arthimetic average) across individual octaves 250–1000 Hz.

Octave (Hz)	BEL	CLE	MUL	ARM	BUN
250	−8.1	−7.5	−7.3	−15.1	−9.6
500	−8.8	−8.3	−8.0	−14.8	−10.0
1000	−8.1	−7.8	−8.0	−14.8	−9.6

J.2.2 Results for ST_{late} on stage

Table J.29: ST_{late} for 1 m measurements at position S1 (arthimetic average) across individual octaves 250–1000 Hz.

Octave (Hz)	BEL	CLE	MUL	ARM	BUN
250	−12.2	−11.6	−11.4	−11.4	−16.2
500	−11.5	−12.4	−13.5	−13.5	−17.6
1000	−11.2	−11.7	−13.0	−15.0	−15.9

Table J.30: ST_{late} for 1 m measurements at position S2 (arthimetic average) across individual octaves 250–1000 Hz.

Octave (Hz)	BEL	CLE	MUL	ARM	BUN
250	−12.0	−11.8	−8.4	−14.6	−14.9
500	−11.5	−11.5	−11.3	−15.7	−17.7
1000	−11.2	−11.4	−12.6	−16.8	−17.3

Table J.31: ST_{late} for 1 m measurements at position S3 (arthimetic average) across individual octaves 250–1000 Hz.

Octave (Hz)	BEL	CLE	MUL	ARM	BUN
250	−11.8	−11.9	−8.7	−12.9	−15.6
500	−10.8	−11.8	−12.0	−15.9	−17.4
1000	−10.7	−12.4	−14.2	−16.8	−16.5

Table J.32: ST_{late} for 1 m measurements at position S4 (arthimetic average) across individual octaves 250–1000 Hz.

Octave (Hz)	BEL	CLE	MUL	ARM	BUN
250	−11.4	−11.5	−12.2	−12.3	−16.6
500	−10.8	−12.4	−14.2	−13.8	−17.6
1000	−11.2	−12.3	−13.3	−14.7	−16.8

Appendix K

Source calibration

To measure G (sound strength) in auditoria the source (Brüel&Kjær omnidirectional loudspeaker type 4295) was calibrated in an anechoic chamber. As only a small anechoic chamber was available a source-receiver distance of 2 m was utilised. Measurements were taken at 15 degree increments around the source to account for source directivity. Measurements were only completed between 0–180 degrees because the source is symmetric around its centreline. These measurements were used to produce a 10 m free-field SPL (corrected for source directivity) which could be used as the reference value for G. To correct for source directivity weightings were computed based on angle. The weightings were computed from the surface area of a segments of a sphere. The segments corresponded the area around a given measurement point, and are shown in Figure K.1. The weightings are summarised in Table K.1.

The 2 m measurement in the anechoic chamber (corrected for source directivity) was modified to the equivalent free field 10 m value using the following equation (taken from ISO-3382-1 [2009])

$$L_{pE,10} = L_{pE,d} + 20\log(d/10) \tag{K.1}$$

where $L_{pE,10}$ is the 10 m free field sound pressure level and $L_{pE,d}$ is the free field sound pressure level at a distance d from the source.

Table K.1: Weightings applied to the measurements around source to account for source directivity

Degree	Area of segment	Weighting
0	0.2	0.004
15	1.7	0.0034
30	3.3	0.065
45	4.6	0.092
60	5.7	0.113
75	6.3	0.126
90	6.6	0.131
105	6.3	0.126
120	5.7	0.113
135	4.6	0.092
150	3.3	0.065
165	1.7	0.0034
180	0.2	0.004
SUM	50.3	1.000

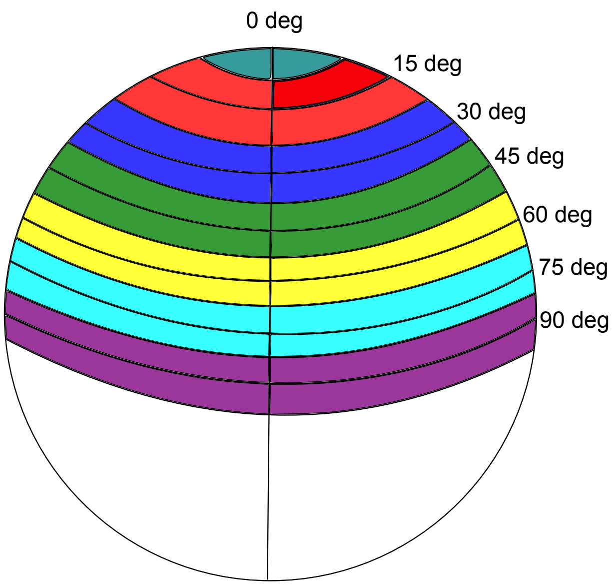


Figure K.1: Sphere split into segments around angles between 0-90 deg (note, the same segment sizes were used between 90-180 deg)